LASER MEASUREMENTS OF TRANSIENT HIGH-STRENGTH ELECTRIC FIELD

R. J. Becker
University of Dayton
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July 15, 1988

FINAL REPORT FOR PERIOD 1 OCTOBER 1985 TO 30 DECEMBER 1987

DISTRIBUTION UNLIMITED

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BOLLING AIR FORCE BASE
WASHINGTON, DC 20332-6448
**Title:** Laser Measurement of Transient (see reverse)

**Author:** Roger J. Becker

**Abstract:**
An experiment was undertaken to determine the usefulness of Rayleigh and Raman scattering as a nonintrusive probe for measuring local electric field strengths. Measurements were made using an argon-ion laser, photon counting electronics, and a 30 kV Stark cell capable of pressurization to 1 MPa. This system was successfully used with He, Ne, Ar, Kr, N₂, CO₂, CF₄, CH₄, SF₆, and CCl₂F₂ gases using a right-angle scattering configuration in which the observation direction was along the axis of polarization of the laser beam. In all cases, a drop was seen in the counting rate for Rayleigh scattering.

A means of calculating the observed effect in Rayleigh scattering was selected based on quantum perturbation theory. This method used both a Coulomb approximation and a single-electron approximation. A computer code was written to implement the perturbation (see reverse side).
Block 11 (Continued)

High-Strength Electric Fields

Block 19 (Continued)
scheme. This code requires input in the form of matrix elements taken from tables in the literature. As not all of the needed entries are available in published form, a second program was being written to extend the published tables. The computer calculations were made to give all contributions to the polarizability including those involving more than one continuum state.

Raman spectra were unchanged by 10 MV/m applied fields. Raman measurements were made in CO$_2$, N$_2$, CCl$_2$F$_2$, SF$_6$, NH$_4$, and liquid benzene. Fourth-rank tensors were found for the D$_{2h}$, C$_{3v}$, O$_h$, C$_{2v}$, and D$_{wh}$ point groups.
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<td>20</td>
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1. OBJECTIVES

This program investigated the utility of a nonintrusive approach to a direct measurement of transient electric fields in plasmas of general interest. The motivation for the program was the fact that current knowledge of the transient behavior of non-equilibrium plasmas is limited. It is known that the behavior of a plasma is a sensitive function of the local electric field strength. Unfortunately, general-purpose methods for measuring transient electric fields in plasma environments with good spatial resolution have not yet been developed. In response to this need, the long-term goal of this research was to devise a nonintrusive method of measuring electric field strengths that (a) is suitable for a wide range of gases of importance, (b) is sensitive, and (c) requires no spectral scanning. The broad research goal was to perform Rayleigh and Raman scattering measurements and to calculate the Rayleigh polarization tensor for atoms and Raman polarization tensors for molecules as a function of applied electric field strength. In short, we anticipated performing quantum perturbation and group theoretical calculations and measurements of scientific value in atomic and molecular physics. It was argued that this work would enable us to measure electric fields in hostile environments with good spatial and temporal resolution. Such measurements are expected to aid in the development of high-performance power devices of various types and to advance the plasma physics of hard-driven and unstable plasmas.

Our specific objectives were to perform Rayleigh measurements in several gases, calculate the Rayleigh polarization tensor for these gases, perform quantum perturbation calculations, conduct experiments on the Stark effect on Raman scattering, and use group theory to predict Raman scattering possibilities.
2. STATUS

Rayleigh measurements were completed on a variety of atomic and nuclear gases, including both isotropic and nonisotropic gases. This work established that Rayleigh scattering is not a feasible electric-field diagnostic for gases or plasmas. The quantum perturbation calculations were completed for all transitions between discrete states, between discrete and continuum states, and between pairs of continuum states.

Raman scattering measurements were conducted on \( \text{N}_2, \text{CO}_2, \text{CCL}_2\text{F}_2, \text{NH}_4, \) and \( \text{SF}_6 \) at pressures up to 120 psi (840 kPa) and field strengths up to 120 kV/cm (12 MV/m). No electric field induced result was detected. Group theoretical calculations of the Stark-induced Raman scattering tensors were made for six-point groups. These calculations showed that Stark-induced changes in Raman spectra should exist in principle. Raman measurements were also made on liquid benzene at field strengths up to 80 kV/cm (8 MV/m). Again, no changes in the recorded spectra were observed.

Rayleigh measurements were made on He, Ne, Ar, Kr, \( \text{N}_2, \) air, \( \text{CO}_2, \text{CF}_4, \text{SF}_6, \text{CH}_4, \) and \( \text{CCl}_2\text{F}_2 \) at pressures of 125 to 150 psi. This selection of gases enabled us to evaluate the pertinence of the degree of isotropy of the target species as well as the ionization potential of the gas. For safety reasons, toxic or flammable gases were not studied. In all cases, a small decrease in the signal, due to the presence of an applied dc electric field at a strength just below the breakdown potential of the gas, was observed. A number of investigations were made as a function of the scattering angle, the solid angle subtended by the collection optics, and the polarization vector of the incident light to determine the nature of the mechanism leading to the drop in signal. These studies suggest that the mechanism is a reduction in the ac polarizability of the gas due to the dc field.
However, the reduction in Tyndall scattering from submicron dust particles due to electrostatic precipitation remains a possibility. The difficulty in making an unambiguous identification of the observed effect was due to the poor signal-to-noise ratio for the experiment. Since the low signal level implies that Rayleigh scattering is not well suited for diagnostics on most plasmas of interest to the Air Force, and since our charter was to determine the feasibility of a technique, rather than pursue scientific research questions in depth, the Rayleigh measurements were terminated and work was initiated to set up Raman studies.

An example of the data from a series of Rayleigh scattering runs is shown in Figure 1. Field-induced cross sections are presented in Table 1. Reduced Rayleigh scattering data for forward and right-angle scattering are given respectively in Tables 2 and 3.

An in-depth theoretical investigation was made. Errors were found in the famous Bates and Damgaard paper containing tables that are used extensively in calculations of atomic interactions. These tables lacked the completeness and accuracy needed for third-order calculation, so we wrote a program to generate improved tables. Calculations of the polarizability and optical transitions between all important pairs of discrete states and between discrete states and the continuum were made. These are the transitions of greatest interest in emission, absorption, and fluorescence spectroscopy, as well as resonant Raman or CARS scattering. The quantum calculations were completed with a treatment of continuum-to-continuum transitions. No significant contribution to the Rayleigh cross section was found from the continuum-to-continuum transitions.
FREON-14 (CF$_4$)

Figure 1. Change in Signal for Rayleigh Scattering from Freon-14 Due to the Application of a 6 MV/m Electric Field.
<table>
<thead>
<tr>
<th>Gas</th>
<th>Field-Induced Cross Section $\frac{d\sigma_F^*}{d\Omega}$ A</th>
<th>Normalized SNR $^*$ $\frac{\Delta \mu}{\sigma_s}$ $F^2 p^{1/2}$</th>
<th>Normalized SNR $^{**}$ (*) $10^{-5} \text{ kV}^2 \text{cm}^4 \text{kPa}^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neon</td>
<td>4.2</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>CF$_4$</td>
<td>0.7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>3.5</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

* Normalized to 10 kV/cm
** Normalized to 10 kV/cm and STP
<table>
<thead>
<tr>
<th>GAS (P)</th>
<th>Mean-Zero Field</th>
<th>Mean-Applied Field</th>
<th>Induced Field (kV/cm)</th>
<th>Statistical Error (σ_s)</th>
<th>SNR (Aμ/σ_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neon (860 kPa)</td>
<td>3431</td>
<td>3343</td>
<td>5</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Freon-14 (860 kPa)</td>
<td>154890</td>
<td>153480</td>
<td>60</td>
<td>320</td>
<td>5</td>
</tr>
<tr>
<td>Nitrogen (860 kPa)</td>
<td>49683</td>
<td>49558</td>
<td>60</td>
<td>43</td>
<td>3</td>
</tr>
<tr>
<td>Air (101 kPa)</td>
<td>5689</td>
<td>5627</td>
<td>60</td>
<td>20</td>
<td>3</td>
</tr>
</tbody>
</table>

*In counts/second*
### Table 3.
REDUCED DATA FOR RIGHT ANGLE SCATTERING

<table>
<thead>
<tr>
<th>GAS (P)</th>
<th>( \mu^*_o )</th>
<th>( \mu^*_f )</th>
<th>( F(\text{KV/cm}) )</th>
<th>( \sigma^*_s )</th>
<th>( \frac{\Delta \mu}{\sigma} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium (860 kPa)</td>
<td>180</td>
<td>175</td>
<td>15</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Neon (860 kPa)</td>
<td>460</td>
<td>437</td>
<td>5</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Argon (860 kPa)</td>
<td>6926</td>
<td>6760</td>
<td>42</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>Krypton (520 kPa)</td>
<td>9312</td>
<td>9213</td>
<td>27</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Nitrogen (860 kPa)</td>
<td>9993</td>
<td>9965</td>
<td>60</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Air (860 kPa)</td>
<td>9265</td>
<td>9222</td>
<td>60</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>10% CH(_4) in argon (690 kPa)</td>
<td>6632</td>
<td>6561</td>
<td>40</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>SF(_6) (760 kPa)</td>
<td>8378</td>
<td>8329</td>
<td>60</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td>CF(_4) (860 kPa)</td>
<td>29979</td>
<td>28652</td>
<td>60</td>
<td>154</td>
<td>9</td>
</tr>
<tr>
<td>CCl(_2F_2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* In counts/second
The code used to make the theoretical predictions was checked against established calculations for oscillator strengths in Helium. Comparisons for several S-p and p-d transitions are given respectively in Tables 4 and 5. These tables show excellent agreement and vindicate our code. The code was then used to predict oscillator strengths for transitions that we were unable to find in the literature, especially transitions involving the continuum. These results are presented in Figures 2 - 6 and Table 6. A detailed description of both the experiment and the calculations is in preparation in a revision of a paper presented earlier to the Journal of Applied Physics. The oscillator strength values are of interest to researchers interested in atomic emission, absorption, and fluorescence. The predicted results for various contributions to the polarizability, which gives the Rayleigh scattering cross section, are given in Table 7. A small increase in the Rayleigh signal is predicted at the field strengths used in the experiment.

The high-pressure Raman experiments in gases were first made with a 1 m Jarrell-Ash monochromator and then repeated using an ISA U-1000 1 m double monochromator. Both the rotational and vibrational spectra were studied. Experiments were conducted to detect changes in the total scattering intensity from allowed lines, changes in polarization properties of these lines, and array-induced activities in lines which are normally Raman inactive. No changes were observed that could not be attributed to statistical fluctuations in the weak Raman signal or to emission from a Townsend current.

As Stark-induced Raman scattering has been observed in semiconductors at field strengths as low as 100 kV/cm (10 MV/m), a review was made of the theoretical possibility of observing an effect. Fourth-rank scattering tensors were calculated for the point groups $D_{6h}$, $C_{3v}$, $O_{h}$, $C_{2v}$, and $D_{oh}$. These calculations showed that Stark-induced changes in the Raman spectra of
TABLE 4.
OSCILLATOR STRENGTHS FOR TRANSITION FROM $1^1S$ TO $N^1P$
IN HELIUM

<table>
<thead>
<tr>
<th></th>
<th>2P</th>
<th>3P</th>
<th>4P</th>
<th>5P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variational</td>
<td>0.27616</td>
<td>0.07344</td>
<td>0.029863</td>
<td>0.015039</td>
</tr>
<tr>
<td>This Work</td>
<td>0.2665</td>
<td>0.07413</td>
<td>0.0306</td>
<td>0.0155</td>
</tr>
<tr>
<td>Percent Error</td>
<td>3.5</td>
<td>1.0</td>
<td>2.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

[9]
### TABLE 5.
OSCILLATOR STRENGTHS FOR TRANSITIONS FROM $2^1P$ TO $3^1D$ IN HELIUM

<table>
<thead>
<tr>
<th></th>
<th>3D</th>
<th>4D</th>
<th>5D</th>
<th>6D</th>
<th>7D</th>
<th>8D</th>
<th>9D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^1P$</td>
<td>0.71016</td>
<td>0.12026</td>
<td>0.04326</td>
<td>0.02095</td>
<td>0.01190</td>
<td>0.007464</td>
<td>0.005015</td>
</tr>
<tr>
<td></td>
<td>0.71103</td>
<td>0.12087</td>
<td>0.04357</td>
<td>0.02113</td>
<td>0.01201</td>
<td>0.007548</td>
<td>0.005062</td>
</tr>
<tr>
<td>$3^1P$</td>
<td>0.02114</td>
<td>0.6481</td>
<td>0.1413</td>
<td>0.05629</td>
<td>0.02890</td>
<td>0.01708</td>
<td>0.01104</td>
</tr>
<tr>
<td></td>
<td>0.02122</td>
<td>0.6484</td>
<td>0.1415</td>
<td>0.05637</td>
<td>0.02895</td>
<td>0.01712</td>
<td>0.01106</td>
</tr>
<tr>
<td>$4^1P$</td>
<td>0.01531</td>
<td>0.0401</td>
<td>0.648</td>
<td>0.1529</td>
<td>0.0636</td>
<td>0.0336</td>
<td>0.02034</td>
</tr>
<tr>
<td></td>
<td>0.01531</td>
<td>0.0402</td>
<td>0.648</td>
<td>0.1529</td>
<td>0.0636</td>
<td>0.0337</td>
<td>0.02036</td>
</tr>
<tr>
<td>$5^1P$</td>
<td>0.00311</td>
<td>0.0393</td>
<td>0.0573</td>
<td>0.670</td>
<td>0.1632</td>
<td>0.0693</td>
<td>0.0373</td>
</tr>
<tr>
<td></td>
<td>0.00311</td>
<td>0.0393</td>
<td>0.0576</td>
<td>0.670</td>
<td>0.1632</td>
<td>0.0693</td>
<td>0.0374</td>
</tr>
</tbody>
</table>

Upper value is from Reference 13. Lower value is from the present calculation.
Figure 2. Plot of Oscillator Strength Distribution in the Continuum for the Ground State of Helium.

[11]
Figure 3. Plot of Oscillator Strength Value at the Spectral Head for np→md transitions vs. n.
Figure 4. Plot of Oscillator Strength Value at the Spectral Head np-ms Transitions vs. n.
Figure 5. Plot of Oscillator Strength Value at the Spectral Head for ns-mp Transitions vs. n.
Figure 6. Plot of Oscillator Strength Distribution in the Continuum for the 2p→Continuum, $l=2$ vs. Energy of the Continuum State.
TABLE 6.
CONTRIBUTIONS TO THE SUM OF THE OSCILLATOR STRENGTHS
FOR $^2\text{P}$ and $^3\text{P}$ HELIUM STATES

<table>
<thead>
<tr>
<th></th>
<th>DISCRETE n≤10</th>
<th>CONTINUUM</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>nd</td>
<td>0.9248</td>
<td>1.0291*</td>
<td>1.9392**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3878**</td>
<td>2.2926**</td>
</tr>
<tr>
<td>ns</td>
<td>-0.1531</td>
<td>0.1578*</td>
<td>0.00472*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.06167**</td>
<td>-0.09136**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.9439*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.2012**</td>
</tr>
<tr>
<td>$^3\text{P}^{**}$</td>
<td>DISCRETE n≤10</td>
<td>CONTINUUM</td>
<td>TOTAL</td>
</tr>
<tr>
<td>nd</td>
<td>0.8897</td>
<td>1.1532</td>
<td>2.0429</td>
</tr>
<tr>
<td>ns</td>
<td>-0.1468</td>
<td>0.0329</td>
<td>-0.1139</td>
</tr>
</tbody>
</table>

* Calculated using the lower bound technique.
** Calculated using the upper bound technique.
<table>
<thead>
<tr>
<th>j</th>
<th>$\alpha_F$</th>
<th>$\alpha_E$</th>
<th>$\alpha_F\cdot\alpha_E^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.499</td>
<td>0.739</td>
<td>1.08x10^{-14}</td>
</tr>
<tr>
<td>3</td>
<td>0.112</td>
<td>0.154</td>
<td>9.26x10^{-7}</td>
</tr>
<tr>
<td>4</td>
<td>4.30x10^{-2}</td>
<td>5.80x10^{-2}</td>
<td>1.49x10^{-5}</td>
</tr>
<tr>
<td>5</td>
<td>2.11x10^{-2}</td>
<td>2.82x10^{-2}</td>
<td>1.33x10^{-4}</td>
</tr>
<tr>
<td>6</td>
<td>1.59x10^{-2}</td>
<td>1.59x10^{-2}</td>
<td>8.06x10^{-4}</td>
</tr>
<tr>
<td>7</td>
<td>7.41x10^{-3}</td>
<td>9.84x10^{-2}</td>
<td>3.62x10^{-3}</td>
</tr>
<tr>
<td>8</td>
<td>4.93x10^{-3}</td>
<td>6.53x10^{-3}</td>
<td>1.48x10^{-2}</td>
</tr>
<tr>
<td>9</td>
<td>3.44x10^{-3}</td>
<td>4.55x10^{-3}</td>
<td>3.81x10^{-2}</td>
</tr>
<tr>
<td>10</td>
<td>2.49x10^{-3}</td>
<td>3.30x10^{-3}</td>
<td>0.104</td>
</tr>
<tr>
<td>Continuum</td>
<td>0.794</td>
<td>2.1824</td>
<td>-2.32x10^{-10}</td>
</tr>
<tr>
<td>Total</td>
<td>1.498</td>
<td>3.202</td>
<td>0.161</td>
</tr>
</tbody>
</table>

↑ Atomic units
symmetric gases are theoretically possible. The calculated tensors are applicable to investigations on other physical phenomena.

Tables 8-10 contain the fourth-rank scattering tensors for the point groups used in the Raman experiment. Although there are 81 components to these tensors, they have been reduced to a six-by-six matrix form. In this format, $T_{lm, nr}$ is reduced to $T_{a,b}$ using the following index reduction

\[
\begin{array}{cccccccc}
1 & 11 & 22 & 33 & 23 & 13 & 12 & \cdot \\
1 & 2 & 3 & 4 & 5 & 6 & & \\
\end{array}
\]

In this format, $T_{11,13}$ reduces to $T_{15}$, $T_{22,26}$ reduces to $T_{26'}$ and so on. The scattering tensors are not totally symmetric. $T_{lm, nr}$ is equal to $T_{ml, nr}$ but not necessarily equal to $T_{nr, lm'}$

In view of the discrepancy between theory and experiment, a final experiment was undertaken with liquid benzene. This experiment also yielded a null result, and established that a Raman scattering, and presumably its companion technique, CARS, will not give a useful measurement of electric field strength at fields on the order of 100 kV/cm (10 MV/m).

In summary, the accomplishments of the program were:

- A change in the Rayleigh scattering cross section was observed in a large variety of gases: He, Ne, Ar, Kr, N$_2$, CH$_4$, CF$_4$, CCl$_2$, CO$_2$, and SF$_6$.

- The change in the Rayleigh signal was studied as a function of the collection angle and the direction of polarization of the incident light.

- Quantitative measurements were made of the field-induced cross sections.

[18]
LASER MEASUREMENT OF TRANSIENT HIGH-STRENGTH ELECTRIC FIELDS

FISCAL REPORT

Expenditures were as follows:

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salaries and Wages</td>
<td>$246,730</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>34,993</td>
</tr>
<tr>
<td>Equipment Rental</td>
<td>4,483</td>
</tr>
<tr>
<td>Communications</td>
<td>1,538</td>
</tr>
<tr>
<td>Travel</td>
<td>5,608</td>
</tr>
<tr>
<td>Equipment</td>
<td>6,474</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$299,827</strong></td>
</tr>
<tr>
<td><strong>Budget</strong></td>
<td><strong>298,859</strong></td>
</tr>
<tr>
<td><strong>Balance</strong></td>
<td><strong>(968)</strong></td>
</tr>
</tbody>
</table>

TABLE 8.
FIELD-INDUCED SCATTERING TENSORS FOR
RAMAN ACTIVITY OF THE $C_s$ AND $C_{2v}$ POINT GROUPS

$C_s$

\[
\begin{array}{cccc}
& & & \\
\text{ahhohh} & 0 & 0 & 0 \\
\text{hhcoohh} & 0 & 0 & c \\
\text{000e0} & a & b & c \\
\text{000g0} & e & f & g \\
\text{hhhood} & 0 & 0 & d \\
\end{array}
\]

$A'$

\[
\begin{array}{cccc}
& & & \\
0 & 0 & 0 & e \\
0 & 0 & b & f \\
0 & 0 & c & g \\
e & f & g & 0 \\
0 & 0 & d & h \\
\end{array}
\]

$A''$

$C_{2v}$

\[
\begin{array}{cccc}
& & & \\
\text{add000} & 0 & 0 & 0 \\
\text{dbd000} & 0 & 0 & 0 \\
\text{ddc000} & 0 & 0 & 0 \\
\text{000h00} & 0 & 0 & 0 \\
\text{000g0} & 0 & 0 & 0 \\
\text{00000f} & 0 & 0 & 0 \\
\end{array}
\]

$A_1$

\[
\begin{array}{cccc}
& & & \\
0 & 0 & 0 & a \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{array}
\]

$A_2$

\[
\begin{array}{cccc}
& & & \\
0 & 0 & 0 & a \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{array}
\]

$B_1$

\[
\begin{array}{cccc}
& & & \\
0 & 0 & 0 & a \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{array}
\]

$B_2$

\[
\begin{array}{cccc}
& & & \\
0 & 0 & 0 & a \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{array}
\]
### TABLE 9.
FIELD-INDUCED SCATTERING TENSORS FOR
THE D_{6h} AND D_{3h} POINT GROUPS

<table>
<thead>
<tr>
<th></th>
<th>D_{6h}</th>
<th></th>
<th>D_{3h}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A_{1g}</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A_{2g}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B_{1g}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B_{2g}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E_{1g}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E_{2g}</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For D_{6h}:
- A_{1g}:
  - \( a \ b \ d \ 0 \ 0 \ 0 \)
  - \( b \ a \ d \ 0 \ 0 \ 0 \)
  - \( d \ d \ c \ 0 \ 0 \ 0 \)
  - \( 0 \ 0 \ 0 \ 0 \ 0 \ 0 \)
  - \( 0 \ 0 \ 0 \ 0 \ 0 \ 0 \)

For D_{3h}:
- A_{1g}:
  - \( a \ a \ b \ 0 \ 0 \ 0 \)
  - \( a \ a \ b \ 0 \ 0 \ 0 \)
  - \( b \ b \ 0 \ 0 \ 0 \ 0 \)
  - \( 0 \ 0 \ 0 \ 0 \ 0 \ 0 \)
  - \( 0 \ 0 \ 0 \ 0 \ 0 \ 0 \)

[20]
| TABLE 10. |
| FIELD-INDUCED SCATTERING TENSORS FOR THE $O_h$ AND $C_{3v}$ POINT GROUPS |

For $O_h$:

- **$A_{1g}$**
  - $\begin{bmatrix} a & b & c & 0 & 0 \\ b & d & c & 0 & 0 \\ c & c & e & 0 & 0 \\ 0 & 0 & 0 & f & 0 \\ 0 & 0 & 0 & 0 & f \end{bmatrix}$

- **$A_{2g}$**
  - $\begin{bmatrix} a & 0 & a & 0 & 0 \\ a & 0 & a & 0 & 0 \\ a & a & 2a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$

- **$E_g$**
  - $\begin{bmatrix} f & b & a & 0 & 0 \\ b & c & a & 0 & 0 \\ f & d & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$

For $F_{1g}(xy)$, $F_{1g}(yz)$, and $F_{1g}(zx)$:

- $F_{1g}(xy)$
  - $\begin{bmatrix} b & a & 0 & 0 & 0 \\ a & 0 & a & 0 & 0 \\ 0 & 0 & c & 0 & 0 \\ 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a \end{bmatrix}$

- $F_{1g}(yz)$
  - $\begin{bmatrix} b & a & 0 & 0 & 0 \\ a & 0 & a & 0 & 0 \\ 0 & 0 & c & 0 & 0 \\ 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a \end{bmatrix}$

- $F_{1g}(zx)$
  - $\begin{bmatrix} b & a & 0 & 0 & 0 \\ a & 0 & a & 0 & 0 \\ 0 & 0 & c & 0 & 0 \\ 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a \end{bmatrix}$

For $F_{2g}(yz)$, $F_{2g}(zx)$, and $F_{2g}(xy)$:

- $F_{2g}(yz)$
  - $\begin{bmatrix} c & f & f & f & f \\ f & e & b+d & f & f \\ f & b+d & e & f & f \\ f & b+d & e & f & f \\ f & b+d & e & f & f \end{bmatrix}$

- $F_{2g}(zx)$
  - $\begin{bmatrix} e & f & b+d & f & f \\ f & c & f & f & f \\ b+d & f & e & f & f \\ b+d & f & e & f & f \\ f & f & f & f & f \end{bmatrix}$

- $F_{2g}(xy)$
  - $\begin{bmatrix} e & b+d & f & f & f \\ b+d & e & f & f & f \\ b+d & e & f & f & f \\ b+d & e & f & f & f \\ b+d & e & f & f & f \end{bmatrix}$

For $C_{3v}$:

- **$A_1$**
  - $\begin{bmatrix} b & c & d & h & 0 \\ c & b & d & h & 0 \\ d & d & a & 0 & 0 \\ h & h & 0 & e & 0 \\ 0 & 0 & 0 & 0 & e \end{bmatrix}$

- **$A_2$**
  - $\begin{bmatrix} c & 2c & 0 & b & 0 \\ 2c & c & 0 & b & 0 \\ 0 & 0 & 0 & 0 & 0 \\ b & b & 0 & a & 2b \\ 0 & 0 & 0 & 2b & a \end{bmatrix}$

- **$E$**
  - $\begin{bmatrix} b & b & c & c & 2b \\ b & b & c & c & 2b \\ b & b & c & c & 2b \\ c & c & a & 0 & 0 \\ c & c & a & 0 & 0 \end{bmatrix}$

[21]
- Computer programs were written to generate confluent hypergeometric wave functions for both discrete and continuum states.

- Oscillator strengths were calculated for discrete-to-discrete and discrete-to-continuum transitions in Helium.

- The contributions to the polarizability of Helium from discrete states were calculated.

- The widely used tables of Bates and Damgaard were extended and calculated more accurately.

- An upper bound on the Stark-induced Raman cross-section of molecules was established.

- Scattering tensors for the quadratic Stark or stress-induced Raman process were calculated for four key point groups.
3. TECHNICAL JOURNALS

A manuscript describing the work on Rayleigh scattering and emphasizing the experiment was submitted to Applied Physics Letters. A revised manuscript is in preparation incorporating comments from the reviewers. A companion list of compiled tables will also be submitted for publication by the American Physical Society. A related paper was presented at the AIAA Aerospace Sciences meeting in Reno in January 1987.
4. **PROFESSIONAL PERSONNEL**

Dr. Roger Becker was the Principal Investigator on the program. Three graduate students obtained their masters' degrees on the program. The titles and the dates of their defenses were:


In addition, Steven Fairchild conducted experimental work on the program from May until August 1986 and Robert Senn worked on the experimental portion of the program from August to May 1986. All five were or are graduate students in the University of Dayton's Electro-Optics Program.
5. INTERACTIONS

The following presentations have been made during the course of the program:


8. Buswell, A. T., "Theoretical Calculations of Stark-Induced Polarizabilities," Poster Session of Applied Spectroscopy (Miami Valley Section), The Ohio State University, Columbus, OH, January 10, 1986.


23. Edward M. Kozak, Jr., "An Analysis of a Possible Probe Technique to Study the Local Electric Field Strengths of Gases," 1988 Joint Spring Meeting of the Ohio Section of the American Association of Physics Teachers, Ohio State University, Columbus, Ohio, April 15-16, 1988.

Communication has also been maintained with Dr. Wan Roh of AFIT and Drs. Bish Ganguly and Alan Garsgadden of the Plasma Physics group at AFWAL.
6. PATENTS

A patent disclosure has been filed on the Rayleigh scattering method, entitled "Rayleigh Scattering Measurement of Electric Field Strengths."
7. ADDITIONAL CONSIDERATIONS

The mission of this program has been to make scientific advances leading to a determination of the feasibility of performing optical measurements of electric field strengths in plasmas. The experimental work has established that Rayleigh scattering is not suitable for this purpose in gases, except possibly at very high pressures, as may occur in some high-power switches. Rayleigh scattering and related elastic scattering processes may be useful in liquids, glasses, and crystalline solids. It would be straightforward to continue the Rayleigh work in condensed matter. If such experiments were undertaken, a full inquiry into the sources of the various noise contributions in the experiment could be made, and a full experimental investigation of the nature of the Stark effect on elastic scattering processes would be completed. The work reported here has laid the groundwork for such an experiment.

The theoretical work undertaken in the program is of great value and should be pursued. These calculations can be extended to most of the atoms in the periodic table in a straightforward manner. This would provide valuable information on selection rule breakdown in emission, absorption, fluorescence, and resonance experiments as well as in Rayleigh scattering. The necessary work for accomplishing most of the needed calculations has already been done; extensions of the calculations involving discrete states to other atoms can proceed on the basis of work already accomplished. The helium calculation can also be extended to other atoms.