

RESIDUAL GAS ANALYSIS IN MAIN RING
TO OBTAIN MEAN-SQUARE SCATTERING ANGLE
AND BEAM LIFETIME

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Purpose

To find the molecular constituents in the vacuum chamber of the main ring and determine the number of molecules/cc of each constituent. Also, to find the mean-square angle through which a 7-GeV beam is multiply scattered, and from this to determine the approximate beam lifetime.

Data

Figs. 1 and 2 show the residual gas analysis samples from approximately 40 magnets near D26 by a mass spectrometer.¹ In Fig. 1 the sensitivity is chosen so that the sum of all the constituents is set to 100. In Fig. 2 the sensitivity is increased by a factor of about 8.5 (determined by the mass-16 peak). An ionization gauge records .21 μ Torr equivalent nitrogen pressure. Table I lists the data that can be extracted from the charts of Figs. 1 and 2.



In order to further analyze the data it is necessary to use the cracking patterns occasioned by the ionization process. These patterns are listed² in Table II. After sorting out the amounts of the various ions present, the percentages of the various molecular constituents can be found. Finally, to convert the percentages of molecular constituents to their contribution to the total pressure reading, it is necessary to use the ionization-gauge sensitivity of the various gases relative to nitrogen. This calibration³ is given in Table III.

Ion Analysis

Possible gases present are: (1) air (N_2 .78, O_2 .21, A .94, CO_2 .03, H_2 .076, Ne .0012, He .0004) where the numbers⁴ shown indicate the fractional abundance present at atmosphere pressure; (2) hydrogen (from gas occluded in vacuum chamber); (3) water vapor; (4) carbon monoxide; (5) methane; (6) ethane; (7) propane; (8) butane; etc. Table I indicates that 98 percent of all constituents are included if one neglects all the hydrocarbons above ethane.

Air is eliminated as a source of residual gas by noting that the mass 14 peak, not all of which can be N^+ , only registers .0057. Similarly, the mass 40 peak, even if attributed entirely to argon, registers only .0012.

The mass group from 25 to 32 can be analyzed in terms of ethane and carbon monoxide. Notice that the peaks 25, 26, 27, 29, 30 are present approximately in the cracking pattern ratios for ethane. The sum of these peaks from Table I (data) is

(.0012 + .0061 + .0094 + .0076 + .0088 = .0331). From Table II (cracking pattern) the sum is (4.5 + 23.4 + 33 + 19.1 + 20.2 = 100.2). Since the cracking pattern for the 28 peak is 100 it follows that the ethane contribution to the 28 peak is $.0331 \times 100/100.2 = .033$. Since the observed peak is .085, the carbon monoxide contribution is .052. The remainder of the cracking pattern for ethane can then be used to give:
 $.0331 \times 1.8/100.2 = .0006$ for $C_2H_2^{++}$, $.0331 \times 5.9/100.2 = .0019$ for $C_2H_4^{++}$, $.0331 \times 8.3/100.2 = .0027$ for $C_2H_6^{++}$,
 $.0331 \times 1.2/100.2 = .003$ for C^+ , $.0331 \times 3.4/100.2 = .0011$ for H_2^+ , and $.0331 \times .74/100.2 = .0002$ for CH_4^+ .

Having found the principal carbon monoxide contribution at mass 28 to be .052, the carbon monoxide cracking pattern provides the following ions: $.052 \times .4/100 = .0002$ for O^+ ,
 $.052 \times 1.4/100 = .0007$ for CO^{++} , and $.052 \times 2.6/100 = .0013$ for C^+ .

The only candidate for mass 17 and 18 is water. Although the observed intensity ratio is .36 and the cracking pattern ratio is .27, the observed sum .363 will be used to find the remaining constituents. Thus one obtains $.363 \times .51/127 = .0015$ for O_2^+ ,
 $.363 \times 5.5/127 = .0158$ for O^+ , and $.363 \times 4.4/127 = .0126$ for H_2^+ .

By subtraction the methane contribution to C^+ is .0034, to CH^+ is .0006, to CH_2^+ is .0031, and to CH_3^+ = .0122. This sum is .0193 and is to be compared with the cracking pattern sum of 109.2. Hence one obtains $.0193 \times 100/109.2 = .0177$ for CH_4^+ , and $.0193 \times .8/109.2 = .0001$ for H_2^+ .

Since no cracking pattern for hydrogen is available, all the constituents for mass 2 and mass 1 are assumed to have the

observed ratio. Thus all the fractions for the postulated ions are found and are listed in Table I under fraction (analysis).

Gas Analysis

Having found the ion analysis except for 2 percent of heavier hydrocarbons the fractional molecular constituency is found by summing all the fractions under a given constituent. Referring to Table IV one sees that $.162 + .248 = .410$ is entered opposite hydrogen, $.0082 + .0126 + .0157 + .098 + .265 + .0014 = .4009$ is entered against water vapor, $.0034 + .0007 + .010 + .052 = .0661$ is entered against carbon monoxide, etc. Since all ions have been analyzed with an instrument whose sensitivity to the amount of each gas is similar to that of an ionization gauge, the actual percentages of the molecules present must be adjusted by the sensitivity factor shown in Table III. For instance, one must divide $.4100$ for hydrogen by $.45$ to obtain $.912$, $.4009$ for water vapor by 1.55 to obtain $.257$, etc. These numbers are adjusted to give 98 percent total.

Finally, to obtain the number of molecules per unit volume of each type at the observed equivalent nitrogen pressure one uses Loschmidt's number $2.687 \times 10^{19}/\text{cc}$ for the number of molecules at 273.16°K and 760 Torr. Thus, for example, the number of molecules per cc is $2.687 \times 10^{19} \times .21 \times 10^{-6}/760 \times 273.16/293 = 6.92 \times 10^9$. Each constituent has its corresponding fraction of this number.

Table V gives the atomic density that is useful in the analysis of the scattering of the beam by residual gas.

Mean Square Angle of Scattering

The rate of increase in the mean square of the angle of scattering projected on to a plane is given⁵ by

$$\frac{\langle \phi^2 \rangle}{\Delta t} = \frac{4\pi r_p^2 c}{\beta^3 \gamma^2} \sum_i n_i Z_i^2 \ln 38360 / \sqrt[3]{A_i Z_i}$$

where $r_p = 1.536 \times 10^{-16}$ cm is the proton radius, n_i is the number of atoms of type i per cc, Z_i and A_i are the atomic number and atomic weight of the i th species of atoms. Thus, using Table V for the atomic composition

$$\frac{\langle \phi^2 \rangle}{\Delta t} = \frac{4\pi(1.536 \times 10^{-16})^2}{(.99299)^3 (8.461)^2} \times 2.9979 \times 10^{10} \cdot \left\{ \begin{aligned} &14.74 \times 10^9 \times 1^2 \ln 38360 \\ &+ 1.22 \times 10^9 \times 6^2 \ln (38360 / \sqrt[3]{12 \times 6}) \\ &+ 1.63 \times 10^9 \times 8^2 \ln (38360 / \sqrt[3]{16 \times 8}) \end{aligned} \right\} = 188.8 \times 10^{-12} \text{ rad}^2 / \text{sec.}$$

Diffusion Rate

The diffusion rate of the quantity $W = (dy/d\theta)^2 + v^2 y^2$

$$D = R^2 \frac{\langle \phi^2 \rangle}{\Delta t},$$

where y is the amplitude and betatron motion, v its tune, and R the average radius. The beam lifetime is given⁶ by

$$t_{1/e} = \frac{1}{D} \cdot \left(\frac{2va}{2.405} \right)^2,$$

where a is the aperture radius. Thus, the resultant lifetime is ($a = 1$ cm)

$$t_{1/e} = \frac{1}{1.888} \cdot \left(\frac{2 \times 20.25 \times 1}{2.405} \right)^2 = 150 \text{ sec.}$$

Table V lists both the mean rate of increase of the square of the projected scattering angle and the beam lifetime assuming that the aperture restriction has a radius of 1 cm.

Conclusion

Since oxygen is the principal contributor to the scattering process and its principal source is water vapor, which is reliably detected by the residual gas analyzer at masses 17 and 18, a rough estimate of the number of scattering centers/cc (oxygen) is to use the mass 17 and 18 fractions of the total equivalent nitrogen pressure. Thus $(.265 + .098) \times 2.687 \times 10^{19} \times .21 \times 10^{-6} / 760 \times 273.16 / 293 = 2.51 \times 10^9 / \text{cc}$, which gives $182 \times 10^{-12} \text{ rad}^2 / \text{sec}$ (compare with 188.8×10^{-12}).

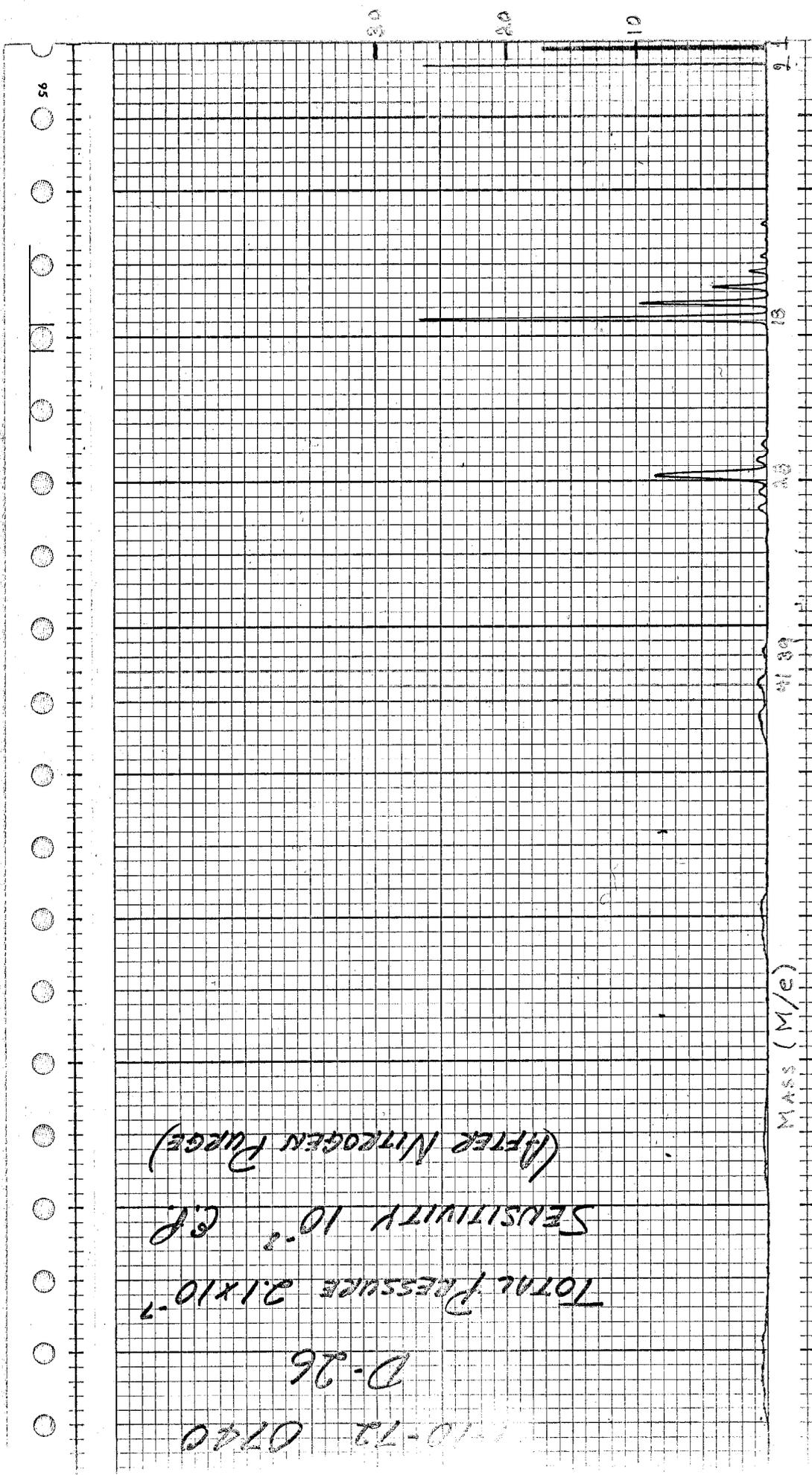
It must be emphasized that the present results pertain only to the test measurement in which the residual gas analysis and pressure are as indicated in Fig. 1. If much higher pressure readings are observed they are most likely associated with an air leak in which case the residual gas analysis would indicate much higher air constituents. The beam lifetime would be significantly reduced in this case; first, because of a higher pressure reading and, secondly, because a much larger percentage of the constituents would have an atomic number near 7.

Acknowledgements

The data in Figs. 1 and 2 were provided by J. Klen. Discussions with J. O'Meara and C. Owen were useful in the utilization of the cracking patterns and ionization gauge sensitivities.

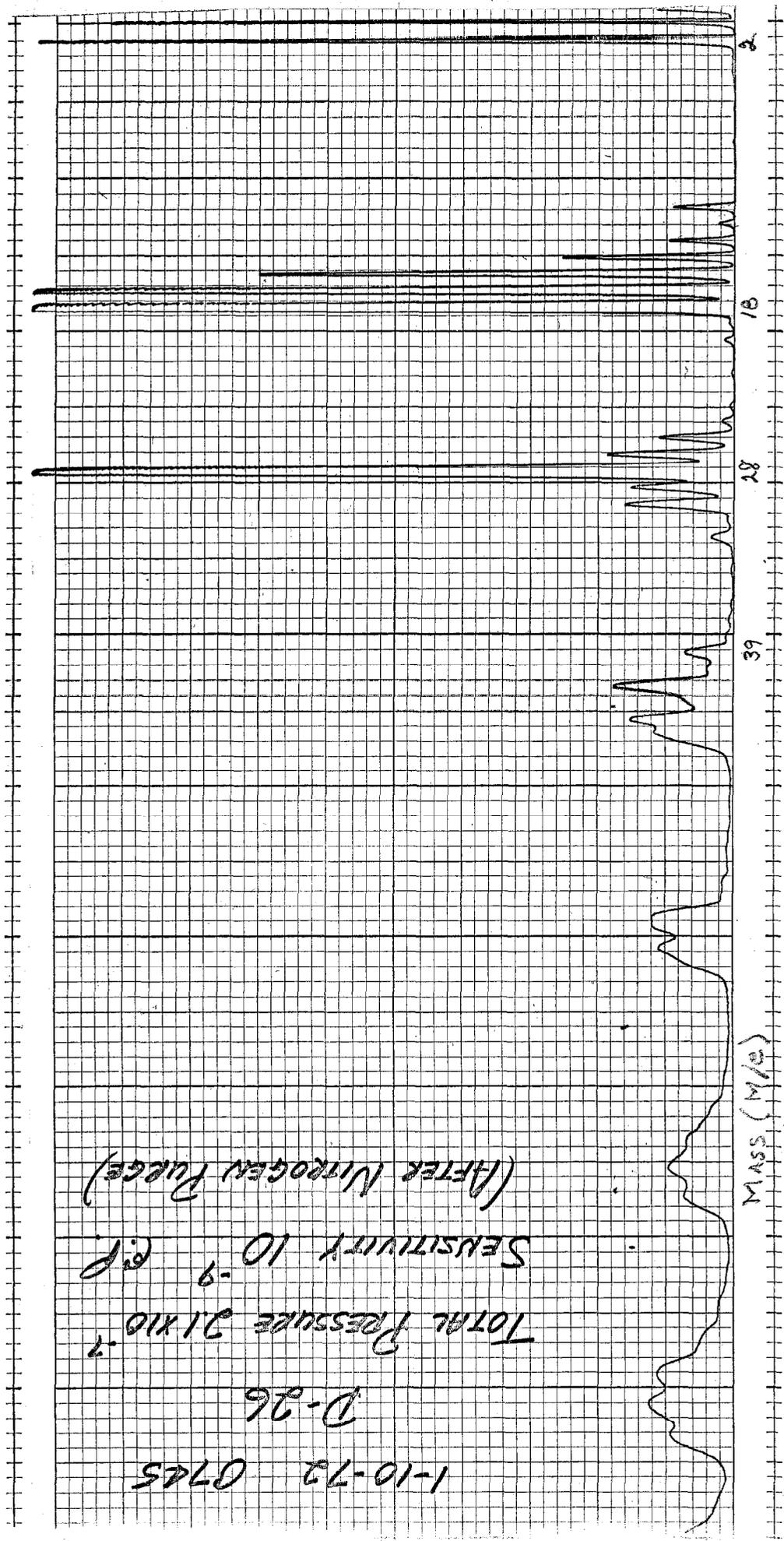
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2. Instruction Manual, Veeco GA-3.
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4. Handbook of Physics and Chemistry, Chemical Rubber Publishing Co.
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10-12-72 0740
D-26
TOTAL PRESSURE 2.1×10^{-7}
SENSITIVITY 10^{-2} C.F.
(AFTER NITROGEN PURGE)

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FIG. 2

TABLE I. Residual Gas Analysis
(.21 μ Torr Equivalent Nitrogen Pressure)

| <u>Source</u> | <u>Mass (M/e)</u> | <u>Ion</u> | <u>Fraction (Data)</u> | <u>Fraction (Analysis)</u> |
|-------------------------------|-------------------|---|------------------------|----------------------------|
| H ₂ | 1 | H ⁺ | .1710 | .1621 |
| H ₂ O | 1 | H ⁺ | | .0082 |
| CH ₄ | 1 | H ⁺ | | .0001 |
| C ₂ H ₆ | 1 | H ⁺ | | .0006 |
| H ₂ | 2 | H ₂ ⁺ | .2620 | .2482 |
| H ₂ O | 2 | H ₂ ⁺ | | .0126 |
| CH ₄ | 2 | H ₂ ⁺ | | .0001 |
| C ₂ H ₆ | 2 | H ₂ ⁺ | | .0011 |
| CH ₄ | 12 | C ⁺ | .0053 | .0003 |
| CO | 12 | C ⁺ | | .0034 |
| C ₂ H ₆ | 12 | C ⁺ | | .0003 |
| CH ₄ | 13 | CH ⁺ | .0012 | .0006 |
| C ₂ H ₆ | 13 | C ₂ H ₂ ⁺⁺ | | .0006 |
| CH ₄ | 14 | CH ₂ ⁺ | .0057 | .0031 |
| C ₂ H ₆ | 14 | C ₂ H ₄ ⁺⁺ | | .0019 |
| CO | 14 | CO ⁺⁺ | | .0007 |
| CH ₄ | 15 | CH ₃ ⁺ | .0149 | .0122 |
| C ₂ H ₆ | 15 | C ₂ H ₆ ⁺⁺ | | .0027 |

TABLE I (continued)

| <u>Source</u> | <u>Mass (M/e)</u> | <u>Ion</u> | <u>Fraction (Data)</u> | <u>Fraction (Analysis)</u> |
|-------------------------------|-----------------------|--|----------------------------|--------------------------------|
| CH ₄ | 16 | CH ₄ ⁺ | } .0410 | .0155 |
| C ₂ H ₆ | 16 | CH ₄ ⁺ | | .0002 |
| H ₂ O | 16 | O ⁺ | | .0157 |
| CO | 16 | O ⁺ | | .0096 |
| H ₂ O | 17 | OH ⁺ | .0980 | .0980 |
| H ₂ O | 18 | OH ₂ ⁺ | .2650 | .2650 |
| C ₂ H ₆ | 25 | C ₂ H ⁺ | .0012 | .0012 |
| C ₂ H ₆ | 26 | C ₂ H ₂ ⁺ | .0061 | .0061 |
| C ₂ H ₆ | 27 | C ₂ H ₃ ⁺ | .0094 | .0094 |
| C ₂ H ₆ | 28 | C ₂ H ₄ ⁺ | } .0850 | .0331 |
| CO | 28 | CO ⁺ | | .0519 |
| C ₂ H ₆ | 29 | C ₂ H ₅ ⁺ | .0076 | .0076 |
| C ₂ H ₆ | 30 | C ₂ H ₆ ⁺ | .0088 | .0088 |
| H ₂ O | 32 | O ₂ ⁺ | .0014 | .0014 |

TABLE II. Cracking Patterns for Some Common Gases
in Vacuum Systems*

| <u>Gas</u> | <u>Composition</u> | | <u>Relative Peak Heights</u> |
|-----------------|-------------------------------|------|----------------------------------|
| | <u>m/e</u> | | |
| N ₂ | N ₂ ⁺ | (28) | 100 |
| Nitrogen | N ₂ ⁺⁺ | (14) | 11 |
| He | He ⁺ | (4) | 100 |
| Helium | He ⁺⁺ | (2) | 1 |
| A | A ⁺ | (40) | 100 |
| Argon | A ⁺⁺ | (20) | 38 |
| Ne | Ne ⁺ | (20) | 100 |
| Neon | Ne ⁺⁺ | (10) | 13 |
| CO | CO ⁺ | (28) | 100 |
| | O ⁺ | (16) | .4 |
| Carbon Monoxide | CO ⁺⁺ | (14) | 1.4 |
| | C ⁺ | (12) | 2.6 |
| CO ₂ | CO ₂ ⁺ | (44) | 100 |
| | CO ⁺ | (28) | 36 |
| | CO ₂ ⁺⁺ | (22) | 5.1 |
| Carbon Dioxide | O ⁺ | (16) | 18.1 |
| | C ⁺ | (12) | 10.4 |

*Based upon 150V electron source. Instr. Manual Veeco(GA-3)

TABLE II (continued)

| <u>Gas</u> | <u>Composition m/e</u> | <u>Relative Peak Heights</u> |
|-------------------------------|---|----------------------------------|
| H ₂ O | O ₂ ⁺ (32) | .51 |
| | H ₃ O ⁺ (19) | .11 |
| | H ₂ O ⁺ (18) | 100 |
| Water | OH ⁺ (17) | 27 |
| | O ⁺ (16) | 5.5 |
| | H ₂ ⁺ (2) | 4.4 |
| CH ₄ | CH ₄ ⁺ (16) | 100 |
| | CH ₃ ⁺ (15) | 89.5 |
| | CH ₂ ⁺ (14) | 12 |
| Methane | CH ⁺ (13) | 5.5 |
| | C ⁺ (12) | 2.2 |
| | H ₂ ⁺ (2) | .8 |
| C ₂ H ₆ | C ₂ H ₆ ⁺ (30) | 20.2 |
| | C ₂ H ₅ ⁺ (29) | 19.1 |
| | C ₂ H ₄ ⁺ (28) | 100 |
| | C ₂ H ₃ ⁺ (27) | 33 |
| | C ₂ H ₂ ⁺ (26) | 23.4 |
| | C ₂ H ⁺ (25) | 4.5 |
| Ethane | C ₂ ⁺ (24) | 1.2 |
| | CH ₄ ⁺ (16) | .74 |
| | CH ₃ ⁺ , C ₂ H ₆ ⁺⁺ (15) | 8.3 |
| | C ₂ H ₅ ⁺⁺ (14.5) | 1.6 |
| | CH ₂ ⁺ , C ₂ H ₄ ⁺⁺ (14) | 5.9 |

TABLE II (continued)

| <u>Gas</u> | <u>Composition m/e</u> | <u>Relative Peak Heights</u> |
|------------|----------------------------|----------------------------------|
| | $C_2H_3^{++}$ (13.5) | .18 |
| CH^+ , | $C_2H_2^{++}$ (13) | 1.8 |
| | C_2H^{++} (12.5) | Trace |
| | C^+ (12) | 1.2 |
| | H_2^+ (2) | 3.4 |

TABLE III. Ionization-Gauge Sensitivity Relative to Nitrogen

| | |
|-----------------|--------------------|
| Hydrogen | .4 - .5 |
| Helium | .14 - .21 |
| Carbon Monoxide | 1.03 - 1.05 |
| Carbon Dioxide | 1.3 - 1.6 |
| Nitrogen | 1.00 (calibration) |
| Oxygen | .80 |
| Water Vapor | 1.1 - 2.0 |
| Neon | .25 - .32 |
| Argon | 1.2 - 1.5 |
| Mercury Vapor | 2 - 3 |

TABLE IV. Molecular Composition of Residual Gas

| | <u>Fraction</u> (Table I) | <u>Gauge Factor</u> (Table III) | <u>Corrected</u> <u>Fraction</u> | <u>Molecules/cc</u> (.21 μ Torr) |
|-------------------------------|------------------------------|------------------------------------|-------------------------------------|---|
| H ₂ | .4103 | .45 | .6689 | 4.63 x 10 ⁹ |
| H ₂ O | .4009 | 1.55 | .1897 | 1.31 x 10 ⁹ |
| CO | .0656 | 1.04 | .0463 | .32 x 10 ⁹ |
| CH ₄ | .0319 | (1.0) | .0234 | .16 x 10 ⁹ |
| C ₂ H ₆ | <u>.0736</u> | (1.0) | <u>.0540</u> | .37 x 10 ⁹ |
| | .9823 | | .9823 | |

TABLE V. Atomic Composition of Residual Gas at .21 μ Torr, Rate of Increase in Mean Square Projected Angle for 7 GeV Proton Beam, and Beam Lifetime (a=1 cm).

| | <u>n</u> (Atoms/cc) | <u>$\langle \phi^2 \rangle / \Delta t$</u> (rad ² /sec) | <u>t_{1/e}</u> (sec) |
|---|-------------------------|--|---------------------------------|
| H | 14.74 x 10 ⁹ | 19.73 x 10 ⁻¹² | 1437 |
| C | 1.22 x 10 ⁹ | 50.84 x 10 ⁻¹² | 558 |
| O | 1.63 x 10 ⁹ | <u>118.23 x 10⁻¹²</u> | <u>240</u> |
| | | 188.80 x 10 ⁻¹² | 150 Net |