national accelerator laboratory

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

S. C. Snowdon

January 18, 1972

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 μTorr equivalent nitrogen pressure. Table I lists the data that can be extracted from the charts of Figs. 1 and 2.

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In order to further analyze the data it is necessary to use the cracking patterns occasioned by the ionization process. These patterns are listed[2] 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 calibration[3] 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 numbers[4] 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 x 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 x 1.8/100.2 = .0006 for $C_2H_2^{++}$, .0331 x 5.9/100.2 = .0019 for $C_2H_4^{++}$, .0331 x 8.3/100.2 = .0027 for $C_2H_6^{++}$, .0331 x 1.2/100.2 = .003 for C^+, .0331 x 3.4/100.2 = .0011 for H_2^+, and .0331 x .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 x .4/100 = .0002 for O^+, .052 x 1.4/100 = .0007 for CO^{++}, and .052 x 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 x .51/127 = .0015 for O_2^+, .363 x 5.5/127 = .0158 for O^+, and .363 x 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 x 100/109.2 = .0177 for CH_4^+, and .0193 x .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 is 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 2.687×10^{19}/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 given[5] by

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

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 ith species of atoms. Thus, using Table V for the atomic composition

$$\frac{\langle \phi^2 \rangle}{\Delta t} = \frac{4\pi (1.536\text{x}10^{-16})^2 \text{ x } 2.9979\text{x}10^{10}}{(.99299)^3 (8.461)^2} \cdot \Big\{ 14.74\text{x}10^9\text{x}1^2 \ \ell n \ 38360$$
$$+ \ 1.22\text{x}10^9\text{x}6^2 \ \ell n \ (38360/\sqrt[3]{12\text{x}6})$$
$$+ \ 1.63\text{x}10^9\text{x}8^2 \ \ell n \ (38360/\sqrt[3]{16\text{x}8}) \Big\} = 188.8\text{x}10^{-12} \text{rad}^2/\text{sec.}$$

Diffusion Rate

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

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

where y is the amplitude and betatron motion, ν its tune, and R the average radius. The beam lifetime is given[6] by

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

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

$$t_{1/e} = \frac{1}{1.888} \cdot \left(\frac{2x20.25x1}{2.405}\right)^2 = 150 \text{ sec.}$$

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 $(.265 + .098) \times 2.687 \times 10^{19} \times .21 \times 10^{-6}/760 \times 273.16/293 = 2.51 \times 10^{9}$/cc, which gives 182×10^{-12} rad^2/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.

References

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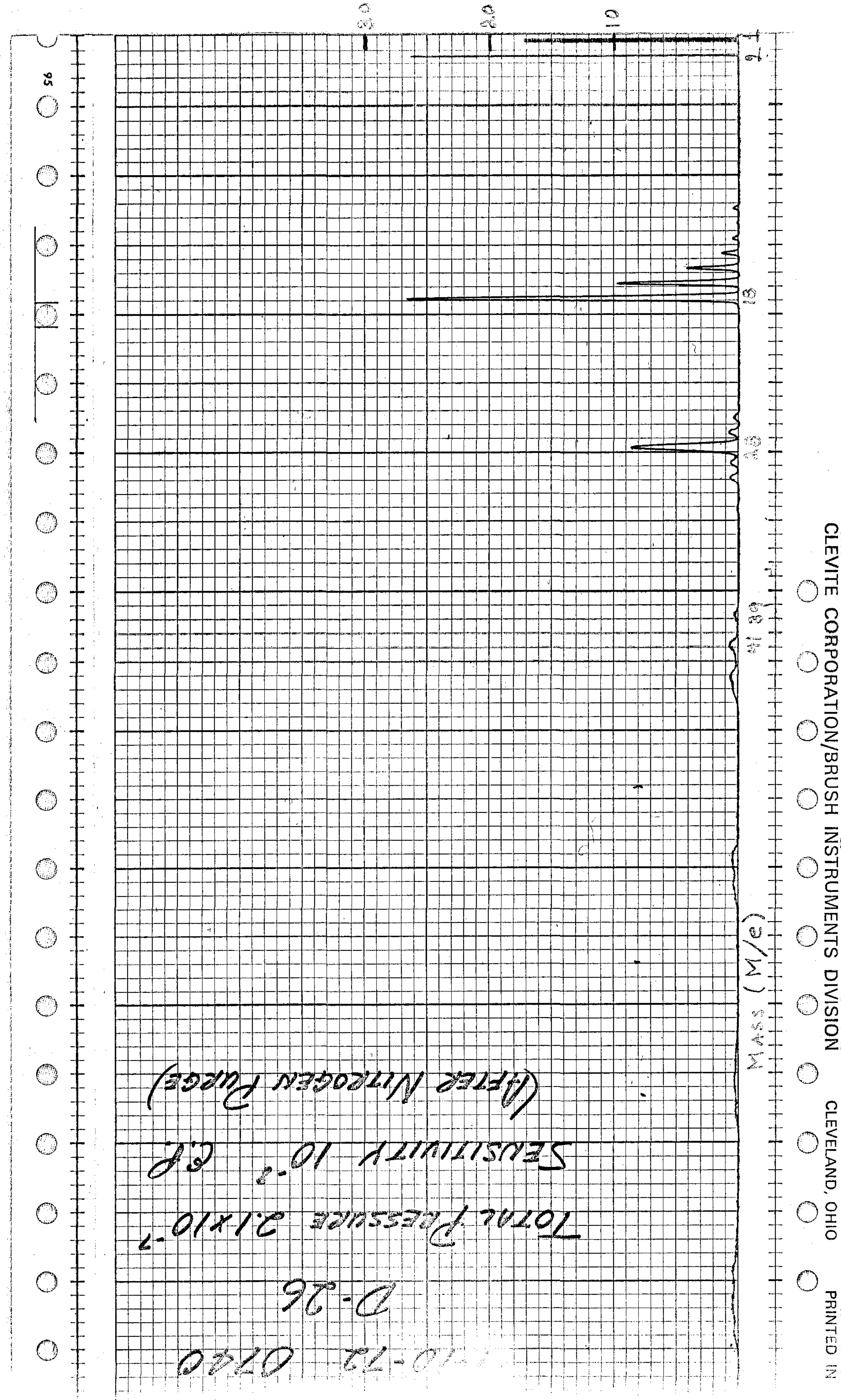

Fig. 1

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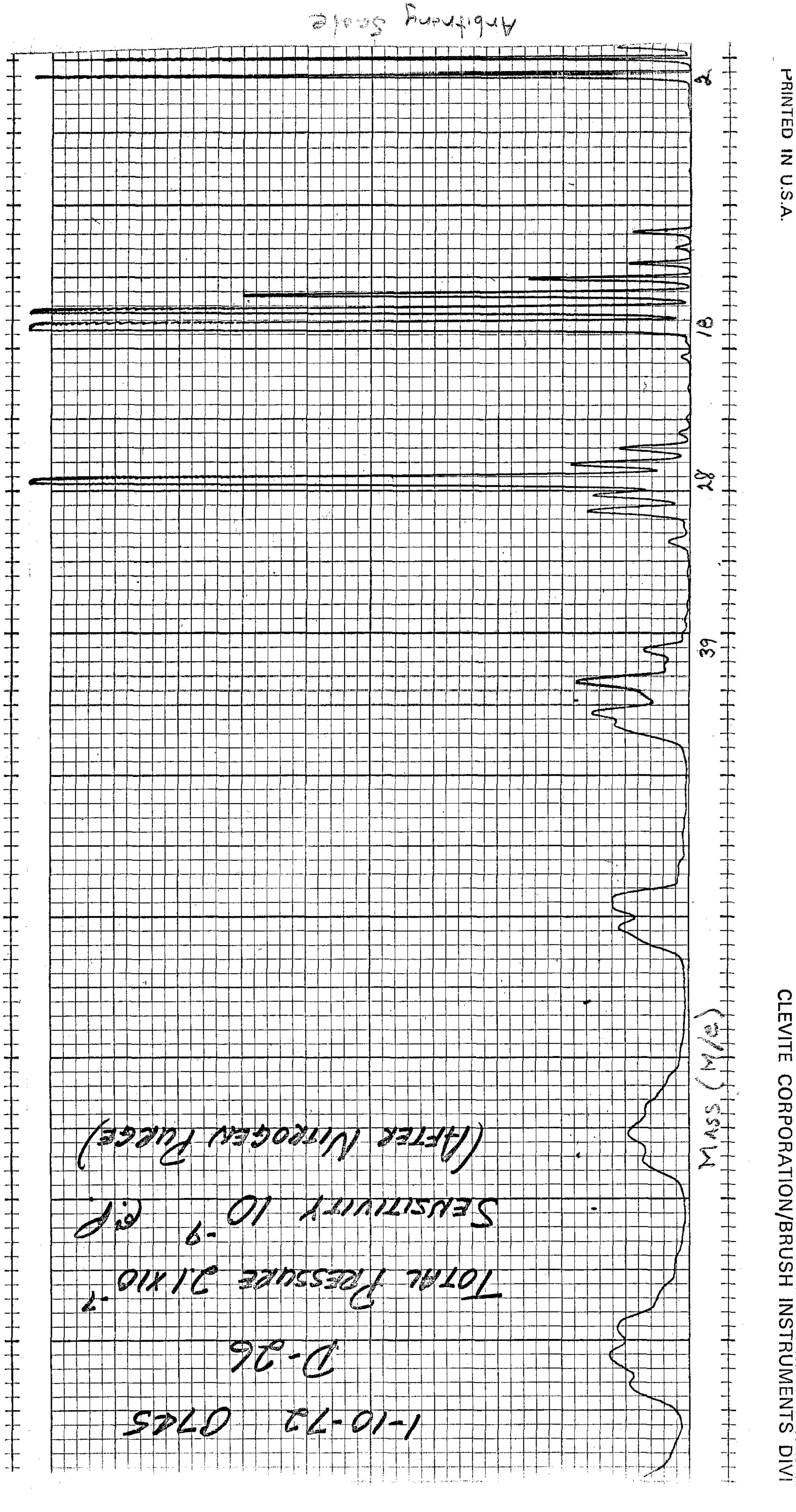

Fig. 2

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

Source	Mass (M/e)	Ion	Fraction (Data)	Fraction (Analysis)
H_2	1	H^+	.1710	.1621
H_2O	1	H^+		.0082
CH_4	1	H^+		.0001
C_2H_6	1	H^+		.0006
H_2	2	H_2^+	.2620	.2482
H_2O	2	H_2^+		.0126
CH_4	2	H_2^+		.0001
C_2H_6	2	H_2^+		.0011
CH_4	12	C^+	.0053	.0003
CO	12	C^+		.0034
C_2H_6	12	C^+		.0003
CH_4	13	CH^+	.0012	.0006
C_2H_6	13	$C_2H_2^{++}$		.0006
CH_4	14	CH_2^+	.0057	.0031
C_2H_6	14	$C_2H_4^{++}$		.0019
CO	14	CO^{++}		.0007
CH_4	15	CH_3^+	.0149	.0122
C_2H_6	15	$C_2H_6^{++}$		.0027

TABLE I (continued)

Source	Mass (M/e)	Ion	Fraction (Data)	Fraction (Analysis)
CH_4	16	CH_4^+	.0410	.0155
C_2H_6	16	CH_4^+		.0002
H_2O	16	O^+		.0157
CO	16	O^+		.0096
H_2O	17	OH^+	.0980	.0980
H_2O	18	OH_2^+	.2650	.2650
C_2H_6	25	C_2H^+	.0012	.0012
C_2H_6	26	$C_2H_2^+$	.0061	.0061
C_2H_6	27	$C_2H_3^+$	.0094	.0094
C_2H_6	28	$C_2H_4^+$	.0850	.0331
CO	28	CO^+		.0519
C_2H_6	29	$C_2H_5^+$	.0076	.0076
C_2H_6	30	$C_2H_6^+$	.0088	.0088
H_2O	32	O_2^+	.0014	.0014

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

Gas	Composition m/e		Relative Peak Heights
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)

Gas	Composition m/e		Relative Peak Heights
H_2O	O_2^+	(32)	.51
	H_3O^+	(19)	.11
	H_2O^+	(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_2H_6	$C_2H_6^+$	(30)	20.2
	C_2H_5	(29)	19.1
	$C_2H_4^+$	(28)	100
	$C_2H_3^+$	(27)	33
	$C_2H_2^+$	(26)	23.4
Ethane	C_2H^+	(25)	4.5
	C_2^+	(24)	1.2
	CH_4^+	(16)	.74
	CH_3^+, $C_2H_6^{++}$	(15)	8.3
	$C_2H_5^{++}$	(14.5)	1.6
	CH_2^+, $C_2H_4^{++}$	(14)	5.9

TABLE II (continued)

Gas	Composition m/e	Relative Peak Heights
	$C_2H_3^{++}$ (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

	Fraction (Table I)	Gauge Factor (Table III)	Corrected Fraction	Molecules/cc (.21 μTorr)
H_2	.4103	.45	.6689	4.63×10^9
H_2O	.4009	1.55	.1897	1.31×10^9
CO	.0656	1.04	.0463	$.32 \times 10^9$
CH_4	.0319	(1.0)	.0234	$.16 \times 10^9$
C_2H_6	.0736	(1.0)	.0540	$.37 \times 10^9$
	.9823		.9823	

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

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