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Measurement of Average Energy Required to Produce an Ion Pair (*W* Value) for Low-Energy Ions in Several Gases

R. HUBER, D. COMBECHER, AND G. BURGER

GSF—Gesellschaft für Strahlen-und Umweltforschung mbH München, Institut für Strahlenschutz, D-8042 Neuherberg, West Germany

HUBER, R., COMBECHER, D., AND BURGER, G. Measurement of Average Energy Required to Produce an Ion Pair (*W* value) for Low-Energy Ions in Several Gases. *Radiat. Res.* **101,** 237–251 (1985).

The *W* value, the mean energy required to form an ion pair, was measured for monoenergetic positive H, He, C, N, O, and Ar ions in the energy range from 1 to 50 keV in air, N_2, CH_4, CO_2, and a tissue-equivalent gas (Rossi–Failla mixture). The *W* values of ions increase, in general, with decreasing energy; only those of H ions show a minimum at an energy of about 25 keV for some gases. The estimated standard deviation of the measurements is about 2% in most cases. © 1985 Academic Press, Inc.

INTRODUCTION

The *W* value of fast-charged particles is the mean energy expended to form an ion pair when particles traverse a gas. If particles lose all their energy in the gas, *W* is the ratio of their initial kinetic energies to the mean number of ion pairs produced in the gas.

W values of ions are used for example in neutron dosimetry with ion chambers. They can be used as an integral quantity in verifying cross section data.

The *W* values for many gases are quite well known for α particles and protons with energies of a few million electron volts. Recently, work has been done for ion energies between 10 and 100 keV (*1–3*). At even lower energies few and contradictory measurements have been performed until now (*4–9*).

The *W* values of H, He, C, O, N, and Ar ions in several gases have been measured. The energies of the ions ranged from 36 eV/u to 50 keV/u. Methane, carbon dioxide, nitrogen, air, and a tissue-equivalent (TE) gas mixture (*10*) were used as target gases.

EXPERIMENTAL SETUP

In this experiment the primary ions dissipate all their energy in the gas of an ionization chamber. The experimental apparatus is shown schematically in Fig. 1. It is similar to that used by Leonard and Boring (*5*). Positively charged primary ions are produced in a hot filament plasma source with an energy spread of 1–2 eV and accelerated with a maximum potential of 50 kV. The ions traverse the ionization chamber, which is 80 cm long and 60 cm in diameter. The primary ion current i_p is measured by using the

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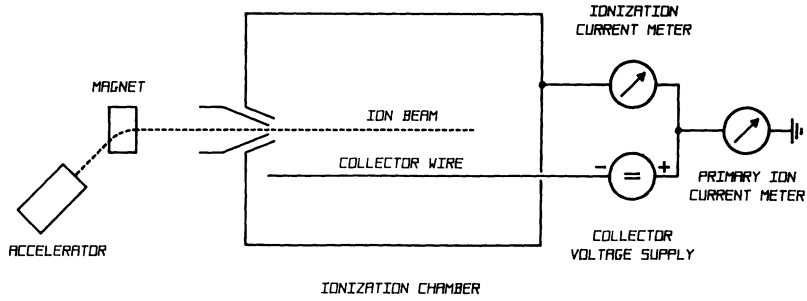

FIG. 1. Schematic diagram of the experimental apparatus.

evacuated chamber as a Faraday cup. With gas in the ionization chamber, the number of ion pairs produced is measured by separating ions and electrons with an electric potential of about 100 V applied between the negative collecting electrode and the wall of the ionization chamber. Primary positive ions as well as positively charged secondary ions are collected by the collecting electrode, a silver wire with a diameter of 0.5 mm, located 6 cm below the axis of the beam. The secondary electrons (δ rays) are stopped in the gas to an energy below the ionization threshold; then they drift to the chamber wall. The current into the wall is equal to the secondary current alone. It is measured by the "ionization current meter."

The primary ions enter the measuring chamber through differentially pumped diaphragms. Details are shown in Fig. 2. The ion beam I is collimated in a heat sink H with a diaphragm 2 mm in diameter. A second diaphragm M with an opening 1 mm in diameter is used as a current monitor. The ions then pass through the differentially pumped volume with a length of 3 cm. Two diaphragms, B and E with openings of 0.1 and 0.4 mm, separated by a distance of 0.5 mm, define the beam entering the ionization chamber. Diaphragm E prevents charged particles from leaving the ionization chamber. In front of the entrance diaphragms a positively charged copper ring R collects electrons emitted from ion impacts on the entrance diaphragm B.

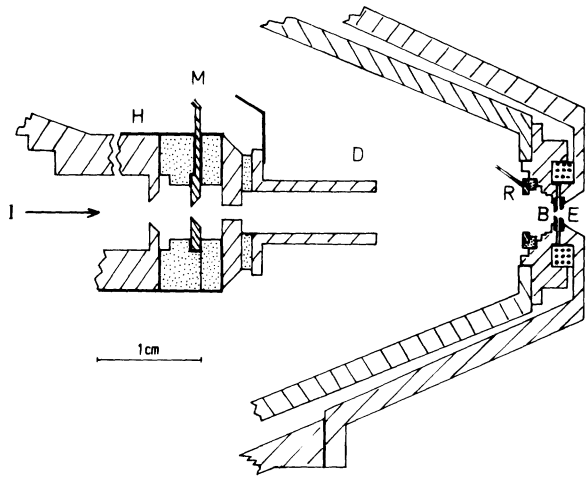

FIG. 2. The entrance diaphragm system.

The potential U_p by which the primary ions are accelerated from zero to their final energy and the primary and secondary ion currents i_p and i_s have been measured. The W value may be calculated easily from these measured values

$$W(\text{eV}) = U_p(\text{V}) \times \frac{i_p}{i_s}. \tag{1}$$

METHOD OF MEASUREMENT

Before the start of a measurement the ionization chamber was evacuated to a pressure lower than 10^{-2} Pa. Then the primary ion current in the chamber was adjusted to a value of 1 to 5×10^{-11} A.

The measurement consists of admitting gas with a steady flow into the chamber. This causes an increase in the gas pressure with time. Measurements are performed only during the time that the pressure increases linearly. The primary and the ionization currents are recorded once a second. After about 80 sec, at a pressure of 100–200 Pa, the experiment is finished. Then the ions lose all their energy in the first quarter of the ionization chamber. In Fig. 3 the ratio $r = i_s/i_p$ of the secondary to the primary current is shown, plotted as a function of the pressure in the ionization chamber. For a vacuum no secondary ions are produced and the ratio is equal to zero. At low pressures it increases with increasing pressure, until the primary ions lose all their energy in the gas. For even higher pressures the ratio should be constant. In fact, in general, it decreases slowly due to perturbing factors discussed later. Over a limited pressure range the decrease is linear with gas pressure. To avoid errors in the measurement which depend systematically on the gas pressure, an extrapolation of the linear range of the curve to pressure zero has been made (*11*). The extrapolated value r_0, lying 0 to 8% above the maximum value, was used for the calculation of the W values with Eq. (1).

While the gas was admitted to the chamber the measurement of the primary current was disturbed by secondary charge carriers passing through the entrance diaphragm E. In some cases the secondary current i_s was more than a thousand times larger than that of the primary ions i_p. If a small fraction of secondary charged particles traverse through the entrance diaphragm E, a current is produced which adds to the measured primary ion current. Therefore the primary ion current could be measured only at zero gas pressure.

The primary current i_p and the current i_M on the monitor electrode M were measured immediately before the gas was admitted to the chamber, and the factor f_M was calculated

$$f_M = i_p/i_M. \tag{2}$$

During the subsequent measurements, while the gas was admitted to the chamber, only the current on the monitor diaphragm M was measured, and it was assumed that the primary current i_p was given by

$$i_p = i_M \times f_M. \tag{3}$$

Actually, in Fig. 3 the ratio

$$r = i_s/(i_M \times f_M) \tag{4}$$

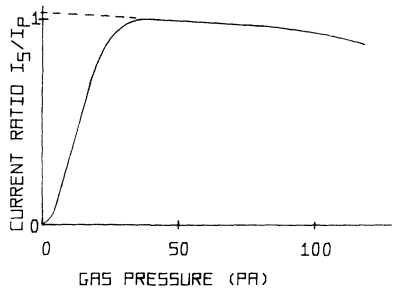

FIG. 3. The dependence of the current ratio, normalized to its maximum, on the gas pressure.

is plotted as a function of the gas pressure. The extrapolated value r_0 of this ratio is used for the calculation of a W value with Eq. (1):

$$W(\text{eV}) = U_p/r_0. \tag{5}$$

RESULTS

Results are shown in Tables I–III and Figs. 4–8. A continuous increase of the W value with decreasing energy of the ions below 10 keV can be seen. The similarity of the W values for C, O, and N ions of equal velocity is remarkable. W values are slightly higher for argon ions and lower for helium ions. Only the W values for protons are distinctly lower. They show a minimum at an energy of about 30 keV in nitrogen, air, and carbon dioxide. The reason may be the high cross section for charge exchange with little energy loss for H ions and atoms at energies below 100 keV (*12, 13*). No significant difference is observed between molecular and atomic ions. It may be assumed that the molecular ion is broken up by one of the first few collisions in the gas.

Our results are compared with those of others in Figs. 9–14. The comparison for hydrogen ions is shown in Figs. 9 and 10. The agreement for CH_4 with the data by Willems *et al.* (*9*) is very good. For CH_4 and TE gas the results join those of Nguyen *et al.* (*3*) and Chemtob *et al.* (*1*) very well above 20 keV. The results of Sidenius (*2*) are somewhat higher, especially in nitrogen. It should be noted that in his experiment the primary particle current was measured with a proportional counter method which may cause some problems at low energies.

In Figs. 11–13 the results for the heavy ions are compared with the results of other authors. Excellent agreement is found with the work by Macdonald and Sidenius (*7*) for N ions in CH_4, and with that by Boring et al. (*14*) for N, O, and Ar ions in N_2. In Figs. 11 and 13 the good match of the Pb recoil ion W values, measured by Cano (*15*), to the values of much lighter ions is remarkable. The results in TE gas for N and C ions are close to the results of Chemtob *et al.* (*1*); for O ions they are between those of Chemtob (*1*) and those of Leonard and Boring (*5*).

In Fig. 14 a comparison is shown of the results for heavy ions in N_2 with a theoretical model by Miller and Boring (*16*). The experimental results agree with the theoretical curve for the Thomas–Fermi potential with modified screening quite well, especially at low energies.

In conclusion, the results of this work show good agreement with the work of others. The knowledge of low-energy ion W values is extended to energies of 0.5 keV, which corresponds to 36 eV/u in the case of N ions.

ERROR DISCUSSION

The uncertainty of the energy of the ions depends on the accuracy of the measurement of the accelerator potential (0.7%), the energy spread of the ions leaving the ion source (1–2 eV), and a gain in energy of the ions in the electric field of the ion collector electrode. The two latter parts of these uncertainties play a role

TABLE I

W-Values of H Ions[a]

Energy (keV/atom)	*W value (eV)*	*Error (%)*		*Energy (keV/atom)*	*W value (eV)*	*Error (%)*	
	H ions in nitrogen						
0.25	193.0	6.0	(H_2)	5.99	34.8	2.3	
0.40	113.0	6.0	(H_2)	9.94	32.4	2.2	(H_2)
0.60	78.7	6.0	(H_2)	9.95	32.3	2.2	
0.74	66.3	5.0	(H_2)	11.95	31.7	2.3	
0.99	56.7	5.0	(H_2)	14.95	31.3	2.1	
1.48	47.8	4.0	(H_2)	19.87	30.9	2.1	
1.49	51.1	4.0		19.96	31.0	2.1	
1.97	43.6	4.0	(H_3)	24.90	30.7	2.0	
2.00	44.0	4.0		30.00	30.3	2.1	
2.49	41.3	4.5	(H_2)	34.95	30.5	2.1	
2.97	39.6	3.5	(H_2)	39.85	30.2	2.1	
2.98	40.5	3.5		44.80	30.1	1.9	
3.94	38.2	2.7	(H_2)	49.75	30.1	2.0	
4.93	37.0	2.5	(H_2)				
5.00	37.0	2.5			H ions in air		
6.90	36.0	2.3		0.51	101.7	6.0	(H_2)
7.89	35.5	2.5		0.99	52.8	5.0	(H_2)
9.81	35.3	1.8	(H_2)	2.02	41.7	4.0	(H_2)
9.83	35.3	2.0	(H_3)	5.01	36.5	2.3	(H_2)
9.84	35.3	1.8		5.01	36.5	2.0	
10.02	35.4	1.8		7.48	35.2	2.0	
14.72	34.3	1.8		9.96	34.9	1.8	
14.72	34.3	1.8	(H_2)	15.01	34.1	1.8	
19.62	33.9	1.7		19.90	33.6	1.7	(H_2)
19.69	33.8	2.1	(H_2)	20.04	33.9	1.8	
20.02	34.0	1.7		24.93	33.5	1.8	(H_2)
24.50	34.0	1.7		25.00	33.5	1.7	
24.68	33.5	1.7	(H_2)	30.00	34.0	1.7	
29.40	33.7	1.6		40.00	34.1	1.7	
34.50	33.8	1.5		49.90	33.9	1.7	
39.40	33.7	1.3					
44.40	34.0	1.4			H ions in CO_2		
49.45	34.4	1.4		1.51	51.0	2.5	(H_2)
49.90	34.4	1.7		3.00	40.0	1.8	(H_2)
				5.02	36.3	1.8	
	H ions in methane			6.99	34.8	1.8	
0.51	88.5	3.4	(H_2)	9.99	34.2	1.8	
1.01	58.2	3.3	(H_2)	20.15	33.5	1.7	
2.02	45.1	3.1		30.00	33.2	1.7	
2.49	41.4	2.3	(H_2)	40.00	33.7	1.7	
3.00	39.5	2.4	(H_2)	49.80	33.4	1.8	
3.01	39.8	3.0					
4.97	35.9	2.2	(H_2)		H ions in TE gas		
4.98	36.3	2.3		0.51	93.1	2.8	(H_2)
5.97	35.0	2.2	(H_2)	0.75	69.7	2.2	(H_3)

(*Continued*)

TABLE I—*Continued*

W-Values of H Ions[a]

Energy (keV/atom)	*W value (eV)*	*Error (%)*		*Energy (keV/atom)*	*W value (eV)*	*Error (%)*	
0.76	69.7	2.2	(H_2)	12.53	32.3	2.5	(H_2)
1.00	61.4	2.1	(H_3)	15.01	32.0	1.8	
1.01	61.2	2.2	(H_2)	16.58	32.0	1.8	(H_3)
1.49	50.0	2.3	(H_2)	20.00	30.9	2.0	(H_2)
2.02	45.1	2.1		20.05	31.4	1.9	
3.00	40.5	2.0		24.90	31.3	1.7	
5.00	36.1	2.7		25.00	31.1	1.8	(H_2)
9.98	33.4	1.8	(H_3)	30.00	30.9	1.8	
9.99	33.3	1.9		40.05	30.7	2.0	
10.02	33.1	1.9	(H_2)	49.95	30.8	1.8	

[a] The value of the energy given in the table for molecular gases is the total energy of the ion divided by the number of atoms in the molecule.

only at very low ion energies. The total uncertainty is lower than 0.8% above 5 keV, and lower than 1.5% in the region from 0.5 to 5 keV.

The measurement of the primary ion current is influenced by sources of error during the measurement in the evacuated measuring chamber and during measurement of the monitor current. The first type of error sources plays only a small role:

—Leakage currents amount to less than 10^{-14} A; they are neglected.

—Electrons which are produced by ion impact on the grounded entrance diaphragm B are collected by the electrode R in Fig. 2. They are captured in the beam by space charge and can enter the ionization chamber through the diaphragm B. Measurements with variable voltages at R show that they would produce an error of 1–3% if they would not be collected. With a voltage of +18 V at R this error may be neglected, too.

—The influence of ions scattered at the edge of the entrance diaphragm may be neglected. This was shown by measurements with diaphragms of different shapes at B and variations in focusing the ion beam.

—The influence of the residual gas pressure in the evacuated chamber may be neglected: the primary current measurement is not influenced by gas pressures lower than 0.1 Pa.

—The incident ions become neutral by charge exchange in collisions with residual gas molecules in the region between the deflecting magnet and the entrance diaphragm. These neutral particles contribute to the energy imparted in the measuring chamber, but not to the measured ion current. The fraction of uncharged particles in the beam was measured by deflecting the charged particles from the entrance diaphragm by means of the deflecting electrodes D shown in Fig. 2. It was measured to be less than 1%, and i_p was corrected correspondingly.

TABLE II

W Values of He and Ar Ions

Energy (keV/atom)	*W value (eV)*	*Error (%)*	*Energy (keV/atom)*	*W value (eV)*	*Error (%)*
	He ions in air				
2.01	90.3	2.4	3.00	87.8	2.5
3.02	78.2	2.2	4.97	70.6	2.4
5.02	65.7	1.9	7.01	62.3	2.3
9.97	54.4	1.7	9.96	55.4	2.1
20.05	46.9	1.8	14.92	50.0	2.2
30.02	43.9	1.8	19.86	46.6	2.2
39.98	42.4	1.8	24.80	44.2	2.0
49.90	41.4	1.9	29.80	42.6	1.9
			34.60	41.3	2.0
	He ions in nitrogen		39.58	40.4	1.9
0.81	172.0	6.0	44.55	39.3	1.9
1.01	146.5	3.8	49.50	38.9	1.9
1.50	118.2	2.1			
1.99	102.3	2.0		He ions in TE gas	
2.49	91.5	2.0			
2.98	84.8	1.8	2.01	97.6	2.0
4.96	69.4	2.0	2.99	81.6	2.1
7.42	60.9	1.8	4.03	73.0	1.8
9.91	56.2	1.7	5.01	65.5	1.8
14.84	51.3	1.7	8.01	57.6	1.9
19.83	48.2	1.8	10.01	54.3	2.0
24.75	46.1	1.8	13.99	50.1	1.8
29.79	44.5	1.7	20.00	44.6	2.2
34.65	43.8	1.9	24.10	43.1	1.9
39.50	43.0	1.7	30.05	42.3	1.8
49.30	41.8	1.7	35.96	41.4	1.7
			39.95	40.9	1.8
	Ar ions in nitrogen		44.90	40.7	1.7
5.01	208.3	3.6	49.90	39.2	2.0
14.91	134.4	3.5			
29.51	105.2	3.7		Ar ions in TE gas	
39.60	97.4	3.6			
			4.01	267.3	1.9
	He ions in methane		10.00	170.6	1.8
1.01	153.8	2.8	20.00	124.4	1.8
2.01	107.1	2.6	40.00	97.5	1.8

Some additional sources of error appear by the indirect measurement of the primary ion current with the monitor diaphragm M during the time when the gas was admitted to the chamber:

—The ratio f_M of the primary particle current and the monitor current changed with time. A linear drift of f_M with time does not influence the result, since the corresponding correction vanishes due to the extrapolation procedure. Measurements

TABLE III

W Values of C, N, and O Ions[a]

Energy (keV/atom)	*W value (eV)*	*Error (%)*	
C ions in nitrogen			
4.90	119.5	3.7	
9.98	91.7	3.6	
19.97	73.8	3.7	
29.77	63.9	3.6	
39.61	59.9	3.7	
N ions in nitrogen			
4.97	127.8	3.1	
4.97	116.3	3.0	(N_2)
9.96	91.9	3.0	(N_2)
9.97	90.5	3.1	
19.72	73.2	3.1	(N_2)
19.89	73.7	3.0	
39.70	60.9	3.1	
O ions in nitrogen			
4.86	133.7	3.6	
19.82	79.6	3.5	
39.50	65.0	3.7	
N ions in air			
1.01	178.0	5.0	(N_2)
2.01	141.0	2.5	
2.01	138.5	4.0	(N_2)
4.01	110.9	3.0	
5.98	97.3	2.1	
8.00	88.0	2.5	
18.94	68.1	1.9	
28.00	60.7	1.7	
42.00	55.3	1.8	
O ions in air			
9.95	86.6	2.1	
16.01	76.0	1.9	
23.90	68.9	1.8	
31.82	65.2	1.8	
40.10	61.4	1.8	
49.85	58.7	1.8	
O ions in CO_2			
16.02	77.2	2.0	
31.90	65.8	1.8	
40.05	61.1	1.9	
49.55	59.8	1.7	
N ions in methane			
1.26	348.7	3.0	(N_2)
2.50	212.9	2.3	(N_2)
2.51	214.5	2.8	
3.00	191.8	2.8	
5.01	142.6	2.6	
5.06	138.9	2.5	(N_2)
7.01	116.2	2.3	
9.92	94.2	2.1	(N_2)
10.00	95.0	2.3	
14.89	78.5	2.1	
19.85	70.3	2.0	
C ions in TE gas			
5.03	127.2	1.9	
9.97	91.5	1.8	
19.95	68.0	1.7	
40.03	54.0	1.7	
49.53	50.7	1.7	
N ions in TE gas			
0.51	476.0	3.2	(N_2)
1.01	298.5	2.1	(N_2)
1.51	238.7	2.1	(N_2)
2.01	202.5	2.3	
2.02	202.0	1.8	(N_2)
2.51	177.5	1.7	(N_2)
3.03	164.4	2.0	
5.01	128.3	1.8	
5.01	126.6	1.8	(N_2)
8.04	104.1	1.9	
9.90	94.6	2.0	(N_2)
10.04	93.6	1.8	
14.93	79.9	1.9	(N_2)
15.01	80.3	1.7	
19.81	72.8	1.7	
19.99	72.5	1.7	(N_2)
24.94	67.4	1.9	(N_2)
24.95	67.3	1.7	
29.95	64.1	1.7	
35.00	60.6	1.8	
39.85	57.0	2.0	
44.86	56.6	1.9	
49.90	54.2	1.9	
O ions in TE gas			
3.03	191.3	2.1	
10.00	98.2	1.9	
20.00	75.3	1.7	
39.93	62.0	1.7	
49.85	57.8	1.7	

[a] The values of the energy given in the table for molecular gases is the total energy of the ion divided by the number of atoms in the molecule.

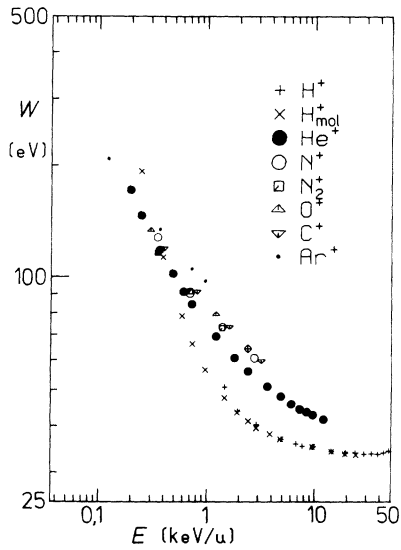

FIG. 4. Results in nitrogen.

were performed only when the accelerator worked under stable conditions. Then only a small long-time drift of f_M was observed which did not influence the results.

—f_M was changed by a spreading of the beam in the differentially pumped region, as primary ions are scattered at the gas flowing out of diaphragm B. This effect is

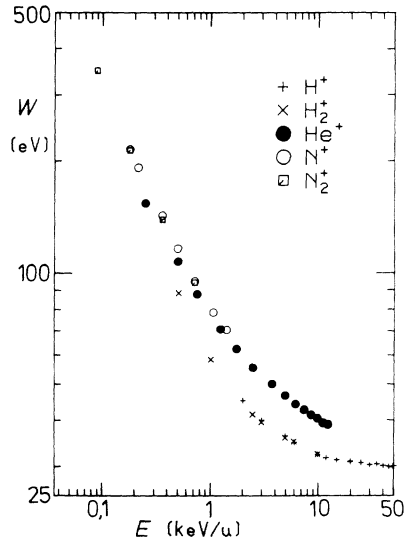

FIG. 5. Results in methane.

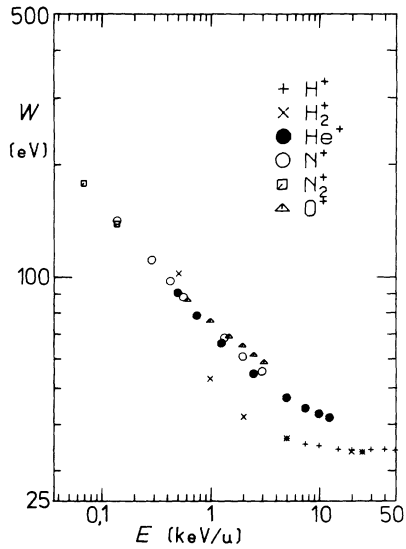

FIG. 6. Results in air.

linear with pressure, and therefore is expected to be cancelled in the extrapolation procedure.

$-f_M$ was influenced by a slight increase in the pressure in the region of the monitor electrode, since this produces additional charge exchanges and ionizations in this region. These effects were also increasing linearly with the pressure.

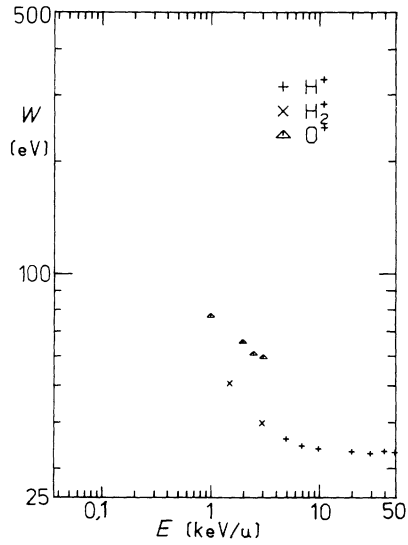

FIG. 7. Results in carbon dioxide.

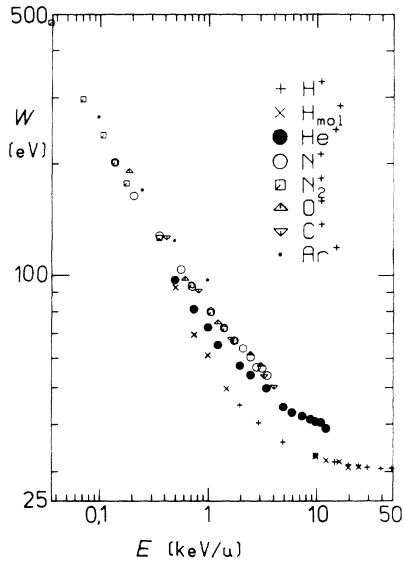

FIG. 8. Results in tissue-equivalent gas.

The total resulting error of the measurement of i_p is estimated to be 0.7%. The error of the measuring instruments is discussed later.

The measurement of the ionization current was influenced by the following perturbing effects:

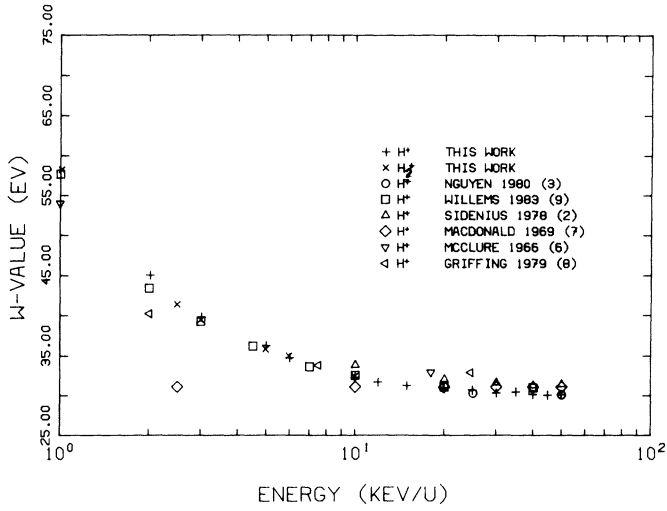

FIG. 9. H ions in methane. Comparison with the results of other authors.

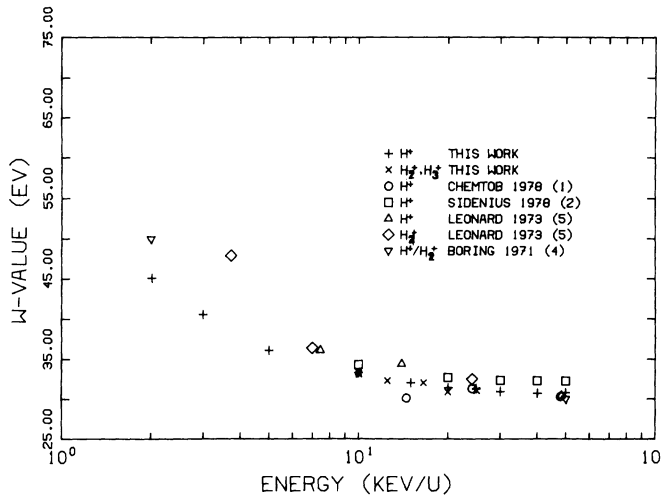

FIG. 10. H ions in TE gas. Comparison with the results of other authors.

—A loss of secondary electrons from the ionization chamber at the entrance diaphragm E lowered the measured ionization current. This effect was linear with pressure; therefore, it vanished in the extrapolation procedure.

—Diffusion of ions to the chamber walls lowered the measured ionization current, too. A calculation of the drift and diffusion velocities showed that it played a role only within a distance of 1 mm from the entrance diaphragm inside the ionization

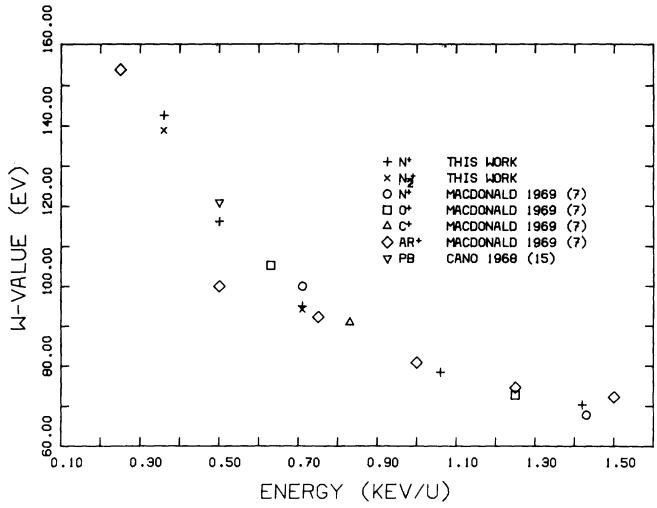

FIG. 11. Heavy ions in methane. Comparison with the results of other authors.

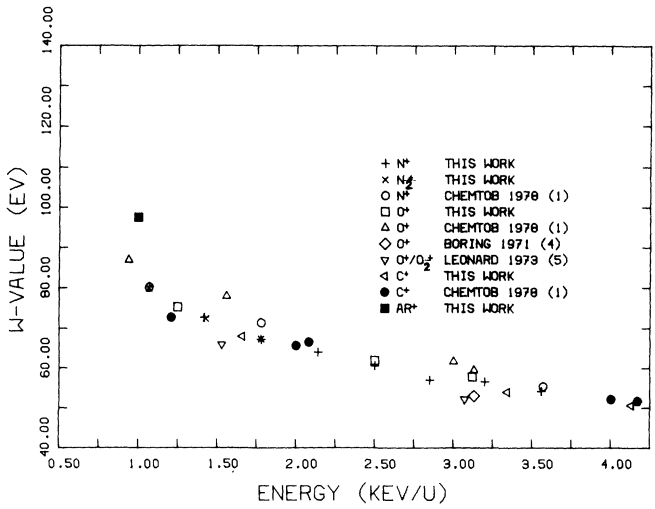

FIG. 12. Heavy ions in TE gas. Comparison with the results of other authors.

chamber. When the range of the particles was 500 mm it produced an error of about 0.2%.

—The recombination of charge carriers was kept small by using low primary ion currents. The extrapolation to zero pressure corrected for possible recombination. Determination of W with 70, 80, 100, 110, 125, and 140 V collection potential showed no systematic trend. Therefore, recombination has been neglected.

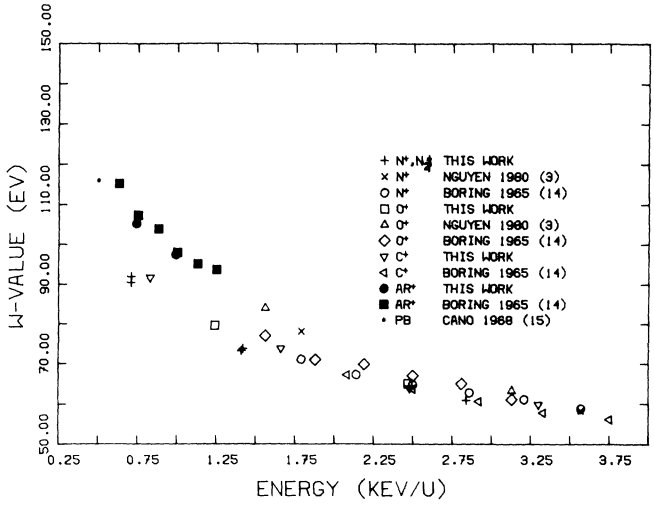

FIG. 13. Heavy ions in nitrogen. Comparison with the results of other authors.

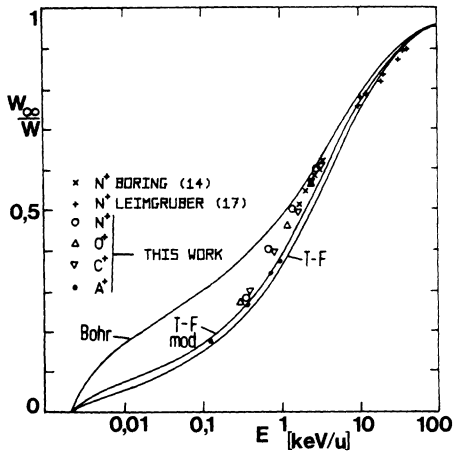

FIG. 14. Heavy ions in nitrogen. The ratio of W_∞ (the constant W value for high-energy electrons) and W is compared with the results of other authors. Straight lines: A theoretical model (*16*) with Bohr, Thomas–Fermi, and modified Thomas–Fermi potential assumed.

—Scattering of primary charged particles into the chamber walls was negligible. For the most part a small number of ions in the backscatter region was collected due to the chamber geometry.

The total error of the ionization measurement is estimated to be 0.5%.

The gas impurities, produced by the rated original impurities of the gases and the measured leakage and desorption rate of the apparatus, were less than 5×10^{-4} in all cases, their influence has been neglected. The error of the measuring instruments was in addition to the above errors. The ratio of the ionization current and the primary ion current was measured with an accuracy of 0.75%.

An important source of uncertainty was the extrapolation procedure. This uncertainty has been determined for each measurement and ranges between 0.5 and 6%.

The standard deviation of measurements extended over several months was 0.8%.

The total error of the measurements is assumed to be the root of the sum of the squares of the particular errors, as they are independent from each other. It is given in Tables I–III.

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