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Review Paper

Electron Impact Cross Section Data for Carbon Tetrafluoride

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Recent electron impact cross section data on CF_4 are critically reviewed and a cross-section data set suitable for plasma modeling purposes is suggested.

KEYWORDS: electron impact, cross sections, carbon tetrafluoride

1. Introduction

In the past several years a number of cross-section data sets for modeling CF_4 have appeared.[1-3] Most of these data sets have relied heavily on swarm data and were incomplete in many respects. Recently cross-section data sets obtained by beam-beam electron scattering experiments have become available. It is the purpose of what follows to critically review these data and to present them in tabular form for use in modeling. Unless otherwise indicated, all results are based on electron scattering from effusive gas jets or electron beam attenuation experiments. All cross section values are given in units of 10^{-20} m^2 (Å^2).

2. Review of Cross Section Data Sets

The analysis and presentation of the cross sections proceed roughly according to increasing electron impact energy starting at the lowest energy.

2.1 *The sub-excitation region: $0 < E_0 < 1$ eV*

Recently Mann and Linder[4,5] have published results from beam-beam experiments in this energy range. Measurements of 72 data points between 0.3 and 1.0 eV were subjected to a modified effective range theory (MERT) analysis which was then used to extrapolate the data to zero energy. The vibrationally elastic data had an energy resolution of 25 meV which was not sufficient to allow resolution of rotationally inelastic scattering. However, assuming that the response functions of the energy analyzers used in the experiment are symmetric functions of the energy loss, information concerning the details of the rotational excitation should be contained in the elastic and momentum transfer cross sections.[6] In this review no attempt was made to extract rotational cross sections from the reported data. In Table I the results are presented for the elastic, momentum transfer, ν_3 vibrational, ν_4 vibrational and total vibrational cross sections. The vibrational cross sections were calculated by means of the Born dipole formulae[7-10]

$$\sigma_{\nu_3} = \frac{1.44}{E_0} \ln \left| \frac{1+\sqrt{1-0.159/E_0}}{1-\sqrt{1-0.159/E_0}} \right| \qquad (1)$$

and

$$\sigma_{\nu_4} = \frac{0.0384}{E_0} \ln \left| \frac{1+\sqrt{1-0.0783/E_0}}{1-\sqrt{1-0.0783/E_0}} \right| \qquad (2)$$

where E_0 is given in eV. The use of these formulae has been justified by comparison with experiment.[4,5,11]

2.2 *Elastic, momentum transfer and vibrational cross sections: $E_0 > 1$ eV*

In this energy range we have taken the experimental values of Boesten *et al.*[11] for the elastic and momentum

Table I. The vibrationally elastic, σ_{el}, momentum transfer, σ_{mt}, and vibrational cross sections for CF_4. The σ_{ν_3} and σ_{ν_4} vibrational cross sections correspond to the infrared allo wed transitions for the asymmetric stretch and bending modes respectively. All cross sections in this and the following tables are in units of 10^{-20} m^2.

E_0 (eV)	σ_{el}	σ_{mt}	σ_{ν_3}	σ_{ν_4}	σ_{vib}
0.00	20.0	10.00			
0.02	6.4	5.3			
0.04	5.0	2.2			
0.06	2.3	1.4			
0.08	1.6	0.57		0.14	0.14
0.10	1.1	0.28		0.39	0.39
0.12	0.85	0.17		0.43	0.43
0.14	0.63	0.15		0.43	0.43
0.16	0.62	0.17	1.43	0.43	1.86
0.18	0.58	0.21			
0.20	0.60	0.30	7.03	0.40	7.43
0.25	0.70	0.50	8.04	0.36	8.40
0.275			8.11	0.35	8.46
0.30	0.90	0.80	8.06	0.33	8.39
0.35	1.2	1.15	7.80	0.30	8.10
0.40	1.6	1.5	7.46	0.28	7.74
0.45	2.0	1.9			
0.50	2.6	2.5	6.77	0.24	7.01
1.00			4.52	0.15	4.67

Table II. The vibrationally elastic, momentum transfer and vibrational cross sections for CF_4 from 1.5 to 100 eV. See caption to Table I. Values in parentheses are from ref. 12.

E_0 (eV)	σ_{el}	σ_{mt}	σ_{ν_3}	σ_{ν_4}	σ_{vib}	σ_{vib}^{exp}
1.5	7.74	6.96	3.43	0.11	3.54	3.3
2.0	8.56	7.14	2.79	0.09	2.88	2.8
3.0	10.5	7.65	2.06	0.06	2.12	2.1
5.0	12.7	8.24	1.39	0.04	1.43	1.2
6.0	13.4	8.62	1.20	0.04	1.24	1.7
7.0	13.4	8.78	1.06	0.03	1.09	5.3
8.0	13.9	9.12	0.95	0.03	0.98	7.3
9.0	15.4	10.2	0.87	0.03	0.90	6.3
10.0	16.6	11.4	0.79	0.02	0.81	4.3
15.0	16.9	13.5	0.57	0.02	0.59	0.76
20.0	17.6 (18.3)	14.1	0.45	0.01	0.46	0.55
35.0	16.7 (16.0)	8.76	0.28	0.01	0.29	
50.0	14.2	6.72	0.21	0.01	0.22	
60.0	13.1	5.84	0.18	0.01	0.19	
100.0	9.84	3.85				

transfer cross sections while the Born dipole approximation has been used to generate the vibrational cross sections with the exception of the cross section labeled σ_{vib}^{exp} which is a combination of the experimental values given in refs. 5 and 11. The excellent agreement between the calculated and the observed total vibrational cross sections between 1.5 and 5 eV is the justification for use of the Born dipole approximation mentioned earlier. The total experimental vibrational cross section values at 15 and 20 eV were obtained by subtracting the total dissociation cross section from the inelastic cross section. The results are displayed in Table II. The values in parentheses at 20 and 35 eV are theoretical values.[12] Note the large difference between the Born dipole vibrational cross section and the experimental cross section between 6 and 10 eV. This difference is due to a vibrational resonance and its composition has been studied by Mann and Linder[5] who showed that the main contributions came from

Table III. The contributions to the vibrational resonances at 8 eV. See the text for further details.

E_0 (eV)	σ_R	$\sigma_R^{\nu_3}$	$\sigma_R^{\nu_4}$	$\sigma_R^{2\nu_3}$
6.0	0.50	0.33	0.11	0.06
7.0	4.20	2.80	0.93	0.47
8.0	6.30	4.20	1.40	0.70
9.0	5.40	3.60	1.20	0.60
10.0	3.50	2.30	0.80	0.40

Table IV. Cross sections for dissociative attachment and ionic dissociation. The subscripts on the sigmas indicate the reaction products.

E_0 (eV)	$\sigma_{CF_3+F^-}$	$\sigma_{CF_2+F_2^-}$	$\sigma_{CF_3^-+F}$	$\sigma_{CF_3^++F^-}$	$\sigma_{CF_2^++F_2^-}$
4		0.00001			
5	0.0008	0.00002	0.0001		
6	0.0060	0.00020	0.0004		
7	0.0110	0.00021	0.0023		
8	0.0110	0.00015	0.0030		
9	0.0040	0.00008	0.0010		
10	0.0008	0.00002	0.0002		
11	0.0004	0.00001			
12				0.0003	0.00002
13				0.0003	0.00003
14				0.0002	0.00001
15				0.0002	0.00001
16				0.0002	
17				0.0002	
18				0.0002	
19				0.0003	
20				0.0003	
25				0.0004	0.00001
30				0.0008	0.00002
35				0.0017	0.00003
40				0.0021	0.00005
45				0.0025	0.00008
50				0.0030	0.00008
50				0.0030	0.00008

the ν_3 and ν_4 fundamentals and the first ν_3 overtone. Furthermore, the various contributions were roughly independent of angle and in the ratio of 6:2:1, respectively. In Table III the vibrational resonance cross section, $\sigma_{\rm R}$, given as the difference between $\sigma_{\rm vib}$ and $\sigma_{\rm vib}^{\rm exp}$, is broken up into its various contributions.

2.3 *Dissociative attachment and ionic dissociation*

Recently new absolute values for dissociative attachment and ionic dissociation have become available.[13] These cross sections are all very small with the largest less than 2×10^{-22} m^2. In Table IV the results are given from 4 to 50 eV. The subscripts on the σ's in the column labels indicate the products formed in the excitation.

2.4 *Dissociative ionization*

The history of measurements of dissociative ionization cross sections is an interesting one. By 1991 two experimental sets of absolute measurements had appeared in the literature,[14,15] but the agreement left much to be desired. It was recognized at about this time that a major problem in such experiments was ion loss in the transmission of ions to the detector due to the often very large ion translational kinetic energies acquired in the breakup process. The situation was corrected in the case of the results presented in ref. 15 by measuring the translational kinetic energy distribution of each detected ion.[16] This allowed these authors to determine the extraction and transmission losses for all ions as functions of their mass. In the case of ref. 15 the data were set on an absolute scale by matching relative intensities to total ionization cross-section measurements made in another laboratory. In the case of ref. 14 the results were set on an absolute scale by carrying out a transmission experiment. In order to do this certain assumptions had to be made. It was assumed that the length of the extracted ion column could be calculated with the SIMION ion trajectory code and the detection efficiency was given by the theoretical values for grid transmission and detector efficiency. Since the publication of ref. 14, extensive work on ion-molecule collisions in the extraction region,[17] the collection efficiency,[18] and other problems has been carried out.

The results of Ma *et al.*[14] and the corrected values of earlier work by Poll *et al.*[15] given in ref. 16 have been averaged and corrected for multiple ion formation.[17,19] The exceptions are CF_3^{2+} and CF_2^{2+} which are corrected values from ref. 14. These data are presented in Tables V and VI. These results include the values given in ref. 17 but with the newly determined absolute detection efficiency of 0.31 which was reported in ref. 18. Since the theoretical value of 0.36 for the instrumental detection efficiency had been used to obtain the previously reported values, the use of the new experimentally determined efficiency of 0.31 resulted in an upward revision of the cross section values in ref. 17 of 16%. The values in parentheses at 100 eV are from Srivastava.[20] The values from the three references cited are in good agreement for the heavier singly charged ions with the values from ref. 20 for the lighter ions being significantly smaller. Since recent work[21] has shown that the lighter ions such as F^+ (note that C^+ is an exception) may have translational kinetic energies in excess of 10 eV, it may be that the larger

Table V. Absolute partial ionization cross sections for the heaviest fragments. See text for further explanations.

E_0 (eV)	$\sigma_{CF_3^+}$	$\sigma_{CF_3^++F^+}$	$\sigma_{CF_3^{2+}}$	$\sigma_{CF_2^++n}$	$\sigma_{CF_2^++F^+}$	$\sigma_{CF_2^{2+}+n}$
16	0.016					
18	0.017					
20	0.384					
25	1.11			0.035		
30	1.93			0.133		
35	2.51			0.216		
40	2.88	0.001		0.228		
45	3.22	0.006	0.002	0.261	0.00 1	0.002
50	3.47	0.009	0.005	0.289	0.00 7	0.006
55	3.65	0.016	0.007	0.308	0.01 4	0.012
60	3.77	0.022	0.013	0.323	0.02 0	0.024
65	3.88	0.028	0.020	0.334	0.02 7	0.037
70	3.94	0.035	0.023	0.340	0.03 5	0.043
75	3.99	0.039	0.026	0.342	0.04 2	0.046
80	4.02	0.045	0.027	0.342	0.05 0	0.050
85	4.04	0.049	0.029	0.346	0.05 4	0.052
90	4.06	0.052	0.030	0.348	0.05 8	0.056
95	4.08	0.057	0.031	0.346	0.06 3	0.060
100	4.09	0.058	0.032	0.345	0.069	0.064
	(3.85)		(0.014)	(0.25)		(0.045)
110	4.11	0.064	0.032	0.346	0.077	0.066
120	4.11	0.065	0.034	0.342	0.078	0.068
130	4.09	0.065	0.035	0.338	0.081	0.069
140	4.03	0.065	0.037	0.335	0.080	0.070
150	3.99	0.067	0.038	0.329	0.082	0.071
160	3.93	0.067	0.038	0.326	0.084	0.071
170	3.89	0.067	0.037	0.322	0.084	0.070
180	3.84	0.066	0.037	0.315	0.084	0.069

differences observed for the lighter ions are caused by different collection efficiencies for the faster ions. In any case these results should be regarded as lower bounds to the actual result. Note also that "n" in the cross-section subscripts in the table headings stands for undetermined neutral products for those cases which may be ambiguous. Note that the multiple ion formation correction is generally small except for the case of the F^+ ion, where 30% of the peak area in a normal mass spectrum comes from double ionization breakup reactions.

2.5 *Neutral fragment ionization cross sections*

Absolute ionization cross sections for CF_3, CF_2, CF, and F have been measured by means of the fast neutral

Table VI. Absolute partial ionization cross sections for CF_4. The lighter fragments. See text for an explanation of how the values were selected.

E_0 (eV)	$\sigma_{CF^+ + n}$	$\sigma_{CF^+ + F^+ + n}$	$\sigma_{C^+ + n}$	$\sigma_{C^+ + F^+ + n}$	$\sigma_{F^+ + n}$
30	0.004				
35	0.044		0.004		0.002
40	0.118		0.032		0.022
45	0.203		0.094		0.076
50	0.253	0.001	0.147		0.139
55	0.278	0.005	0.172		0.173
60	0.312	0.014	0.208		0.233
65	0.340	0.027	0.241	0.001	0 .287
70	0.355	0.041	0.261	0.003	0 .314
75	0.360	0.055	0.268	0.008	0 .328
80	0.363	0.072	0.273	0.014	0 .334
85	0.361	0.082	0.281	0.018	0 .349
90	0.362	0.097	0.288	0.022	0 .362
95	0.362	0.112	0.298	0.027	0 .375
100	0.364	0.123	0.298	0.034	0. 387
	(0.19)		(0.25)		(0.16)
110	0.355	0.149	0.297	0.045	0. 394
120	0.349	0.162	0.292	0.053	0. 390
130	0.330	0.174	0.283	0.063	0. 390
140	0.315	0.181	0.280	0.068	0. 391
150	0.300	0.190	0.276	0.072	0. 381
160	0.287	0.198	0.271	0.077	0. 379
170	0.281	0.200	0.265	0.080	0. 369
180	0.270	0.207	0.251	0.090	0. 349

Table VII. Absolute ionization cross sections for CF_3. See text for further details.

E_0 (eV)	$\sigma_{CF_3 \to CF_3^+}$	$\sigma_{CF_3 \to CF_2^+ + F}$	$\sigma_{CF_3 \to CF^+ + n}$	$\sigma_{CF_3 \to F^+ + n}$
10	0.02			
12	0.04			
14	0.10			
16	0.15			
18	0.17	0.06		
20	0.20	0.17		
22	0.27	0.25	0.04	
24	0.30	0.31	0.10	
26	0.32	0.34	0.15	
28	0.32	0.40	0.20	
30	0.33	0.49	0.26	(0.05)
35	0.34	0.58	0.36	
40	0.35	0.63	0.40	(0.28)
45	0.36	0.65	0.45	
50	0.36	0.67	0.53	
55	0.37	0.71	0.58	
60	0.37	0.72	0.62	(0.35)
65	0.38	0.74	0.65	
70	0.38	0.76	0.68	0.35
80	0.37	0.79	0.70	(0.35)
90	0.37	0.78	0.72	
100	0.35	0.78	0.73	(0.34)
120	0.34	0.78	0.75	(0.32)
140	0.33	0.77	0.77	(0.30)
160	0.32	0.76	0.75	(0.28)
180	0.31	0.74	0.74	(0.26)
200	0.29	0.73	0.72	(0.24)

beam technique[22-24] and the data are presented in Tables VII and VIII. The subscripts on the σ's indicate the process involved and "n" stands for what should mainly be neutral products in cases where ambiguity exists. It is of interest to point out that the CF_4 molecule is one of the very few for which such extensive data on fragment ionization potentials exists.

The values in parentheses for F^+ production from CF_3 and CF_2 in Tables VII and VIII were taken from graphs given in ref. 23 and should be considered as very rough estimates. An upper limit of 0.1×10^{-20} m^2 at 70 eV electron impact energy was given for C^+ production from all three molecules CF_3, CF_2, and CF. The cross section for F^+ production from CF was reported as $(0.25\pm0.1)\times 10^{-20}$ m^2 at 70 eV electron impact energy.

2.6 *Total dissociation and neutral dissociation cross sections*

For CF_4 it is possible to obtain the total dissociation cross section by taking the total cross section[25-27] and subtracting from it the elastic cross section.[11,28] The results of this procedure are presented in Table IX and compared with the results from a direct experimental measurement of the total dissociation cross section by Winters and Inokuti.[29] The agreement would seem to confirm that the original measurements of Winters and Inokuti[29] are correct. The unmarked σ_{tot} values are from ref. 25, the asterisked values are from ref. 26, and the values in parentheses are from ref. 27. The values for the integral elastic cross section are taken from ref. 11 for incident energies from 15 to 60 eV and from 75 to 100 eV the

Table VIII. Absolute ionization cross sections for CF_2, CF, and F. See text for further details.

E_0 (eV)	$\sigma_{CF_2\to CF_2^+}$	$\sigma_{CF_2\to CF^++F}$	$\sigma_{CF_2\to F^++n}$	$\sigma_{CF\to CF^+}$	$\sigma_{F\to F^+}$
10	0.05				
12	0.15			0.03	
14	0.26			0.13	
16	0.39	0.09		0.23	0.04
18	0.47	0.18		0.33	0.03
20	0.64	0.23		0.45	0.07
22	0.69	0.31		0.55	
25	0.75	0.38		0.66	0.19
30	0.87	0.48	(0.04)	0.81	0.34
35	0.92	0.77		0.93	0.43
40	0.98	0.88	(0.20)	1.01	0.48
45	0.99	0.97		1.08	0.61
50	1.01	1.02		1.15	0.68
55	1.03	1.08		1.18	0.72
60	1.03	1.11	(0.55)	1.23	0.78
65	1.05	1.16		1.25	0.83
70	1.03	1.19	0.60	1.25	0.87
80	0.99	1.22	(0.60)	1.26	0.90
90	0.96	1.25		1.25	0.95
100	0.91	1.28	(0.55)	1.23	0.98
120	0.86	1.24	(0.50)	1.14	0.98
140	0.78	1.18	(0.45)	1.04	0.96
160	0.67	1.12	(0.40)	0.90	0.96
180	0.58	1.05	(0.35)	0.79	0.92
200	0.49	0.93	(0.28)	0.67	

Table IX. Estimation of the total dissociation cross section from the total cross section and the vibrationally elastic cross section. See text for further details.

E_0 (eV)	σ_{tot}	σ_{el}	$\sigma_{tot}-\sigma_{el}$	σ_{dissoc}^{tot-el}	σ_{dissoc}
15	18.02	16.92	1.1	0.5	0.21
	(18.17)		(1.3)	(0.7)	
20	19.03	17.63	1.4	0.8	0.85
	(19.38)		(1.8)	(1.3)	
35	19.77	16.72	3.1	2.8	3.0
	(20.77)		(4.1)	(3.8)	
50	19.44	14.24	5.2	5.0	4.3
	(20.34)		(6.1)	(5.9)	
60	20.83*	13.06	7.7	7.5	4.7
	(19.90)		(6.1)	(5.9)	
75	19.90*	12.3**	7.6	7.5	5.24
	(18.70)		(6.4)	(6.3)	
100	18.52*	12.2	6.3	6.2	5.55
	(17.1)		(4.9)	(4.8)	
150	16.26*	10.8	5.5	5.4	5.51
	(14.2)		(3.4)	(3.3)	

results are an average of the cross sections reported in refs. 11 and 28. The double asterisk in this column signifies the beginning of the change over to an average value. The results in column 5 of the table were obtained from the previous column by subtraction of the vibrationally inelastic scattering as given by the Born dipole approximation (see the last column in Table II). The last column in Table IX presents the direct measurements of the total dissociation cross section given in ref. 29.

Recently direct measurements of the absolute cross sections for the production of CF_3, CF_2 and CF have been reported.[30] These values are shown in Table X. The consistency of these results can be tested in the near-threshold region by adding them together and adding the result to the total dissociative ionization counting cross section to obtain the total dissociation cross section for energies below 40 eV. This can be done because no fluorine ion production occurs below 40 eV. The values in parentheses are recommended values which reproduce the total dissociation cross section below the ionization threshold and when added to the dissociative ionization cross section agree with the total dissociation cross section above the ionization threshold.

In Table XI estimates of the total neutral dissociation

Table X. Neutral production cross sections for CF_4. The p in the subscripts of sigma in the column headings stands for neutral products below 40 eV and neutral plus ionic above it. See text for further explanation.

E_0 (eV)	σ_{CF_3+p}	σ_{CF_2+p}	σ_{CF+p}
13	0.0003		
	(0.02)		
14	0.0011		
	(0.09)		
16	0.0040	0.0014	
	(0.15)	(0.05)	
18	0.0097	0.0041	
	(0.29)	(0.12)	
20	0.022	0.0098	0.0034
	(0.29)	(0.13)	(0.04)
25	0.049	0.0233	0.0117
	(0.28)	(0.14)	(0.07)
30	0.076	0.0364	0.020
	(0.24)	(0.11)	(0.06)
35	0.082	0.049	0.029
	(0.14)	(0.08)	(0.05)
40	0.096	0.0583	0.040
45	0.122	0.068	0.052
50	0.146	0.080	0.065
55	0.171	0.094	0.083
60	0.192	0.105	0.105
65	0.207	0.113	0.130
70	0.228	0.123	0.151
75	0.257	0.137	0.167
80	0.276	0.150	0.182
85	0.280	0.164	0.196
90	0.288	0.175	0.205
95	0.302	0.186	0.208
100	0.322	0.195	0.209
110	0.376	0.206	0.210
120	0.390	0.212	0.210
130	0.390	0.215	0.209
140	0.381	0.213	0.207
150	0.371	0.207	0.204
160	0.365	0.202	0.202
170	0.358	0.196	0.198

Table XI. Absolute total cross sections for dissociation into all neutral fra gments. See text for further explanation.

E_0 (eV)	$\sigma_{neutdis}$ (ref. 30)	$\sigma_{neutdis}$ (ref. 29)
13	0.0003	0.03
14	0.0011	0.09
16	0.0054	0.20
18	0.0138	0.42
20	0.035	0.44
25	0.084	0.49
30	0.132	0.41
35	0.160	0.27
40	0.136	
45	0.166	
50	0.152	0.1 ± 0.2
55	0.175	
60	0.169	
65	0.163	
70	0.188	
75	0.233	
80	0.264	
90	0.306	
100	0.339	
150	0.401	

cross section are given. The values labeled ref. 30 were obtained by summing the values for CF_3, CF_2 and CF production given in ref. 30 and subtracting out the absolute ionization cross-section for the production of F^+ given in Table VI. The values labeled ref. 29 were obtained by subtracting a 0.03×10^{-20} m^2 background from the values given in ref. 29 and then subtracting the total counting dissociative ionization cross section. The latter is the sum of all entries in Tables V and VI for each impact energy. Below 30 eV the results diverge sharply. Above 30 eV the dissociative ionization cross section approaches the total dissociation cross section so that the error in taking the difference between the two sets of measurements makes it impossible to obtain useful results. The results for the neutral dissociation inferred from the data in ref. 30 do not seem unreasonable. For electron impact energies above 35 eV the recommended neutral dissociation values are those given in column 2 of Table XI. The higher values given in column 3 of Table XI are consistent with two independent experimental determinations of the total dissociation cross section. It will be interesting to see if plasma modeling using the two disparate sets of neutral dissociation cross sections below 35 eV will yield different answers.

In Table XII the estimated total dissociation cross section using the data of ref. 30, σ_{totdis}, is compared with the results of Winters and Inokuti,[29] σ^{WI}_{totdis}. The column labeled FACTOR in Table XII indicates what the total results of ref. 30 would have to be multiplied by to obtain agreement with ref. 29 assuming that the total counting dissociative ionization cross section is correct. Note also that a background contribution of 0.03×10^{-20} m^2 has been subtracted from the values given in ref. 29. Because the results given in ref. 30 appear to be too small near threshold it is recommended that the values given in parenthesis in Table X be employed in modeling. These results were obtained by multiplying the results given in ref. 30 by the factor given in the last column of Table XII. Note that it does not seem reasonable that the

Table XII. Comparison of total dissociation cross sections in the threshold region. Column two is the sum of the cross-sections given in ref. 30 and column three is the total counting ionization cross sections.

E_0 (eV)	σ_{CF_n+p}	$\sigma_{CF_n^+ +p}$	σ_{totdis}	σ^{WI}_{totdis}	FACTOR
14	0.0011		0.0011	0.09	82
16	0.0054	0.016	0.021	0.22	37
18	0.0138	0.017	0.031	0.44	30
20	0.035	0.384	0.42	0.82	13
25	0.084	1.15	1.23	1.64	5.8
30	0.132	2.06	2.19	2.47	3.1
35	0.160	2.73	2.90	3.00	1.7

only remaining unobserved neutral fragment, atomic carbon, should be able to explain the large deviations below 40 eV.

2.7 *Fluorescence yields and metastable state formation*

The emission spectra of electron impact excited CF_4 is dominated by a strong continuum emission band[31] stretching from 200 nm to 500 nm with a maximum integrated cross-section at 100 eV of 0.45×10^{-20} m^2. Evidence has recently been obtained[31] that the species responsible for the emission is the CF_3^+ ion and that the threshold for the excitation of the state leading to the emission is 23.6 eV. In Table XIII the cross-section as a function of electron impact energy and the relative emission intensity as a function of the wavelength are given.

The electron impact production of metastable fluorine with a threshold at 40 eV has also been recently observed.[32] No absolute cross-section values were obtained but the kinetic energy distribution of the metastables was observed. Metastables with kinetic energies in the range of 9 to 18 eV attain a maximum in their production cross section at an electron impact energy of about 250 eV. Metastables in the kinetic energy range of 3.3 to 4.7 eV attain peak production occurring at 140 eV while the complete distribution peaks at 180 eV.

Table XIII. Fluorescence cross sections and relative intensity of emitted light as a function of wavelength.

E_0 (eV)	$\sigma_{CF_3^+ \to h\nu+p}$	λ (nm)	$I_{rel}(\lambda)$
23.6	0.014	200	1
25	0.17	225	27
37	0.28	250	48
50	0.33	275	101
62	0.41	300	128
75	0.44	325	78
87	0.45	350	45
100	0.45	375	31
112	0.46	400	24
125	0.46	425	15
137	0.46	450	9
150	0.45	475	6
162	0.45	500	3
175	0.45		

2.8 *The angular dependence of the vibrationally elastic scattering*

A simple model for the angular dependence of the vibrationally elastic scattering can be taken as

$$\frac{d\sigma(\theta)}{d\Omega} = a_0\left[1 + b_1\left(1+\cos\theta\right)^{n_1} + b_2\cos^{n_2}\theta\right] \quad (3)$$

where the five parameters can be determined from the data given in refs. 4 and 11. In Table XIV approximate values for the angle resolved cross section, $d\sigma(\theta)/d\Omega = \sigma(\theta)$, are given for $\theta = 0°$, 90°, and 180° as a function of the incident electron kinetic energy. The values in parentheses in Table XIV were taken from ref. 4 while the remaining values come from ref. 11. Values for σ_{el} and σ_{mt} can be obtained from Tables I and II. The expressions for these cases can be written as

$$\sigma_{el} = 4\pi a_0\left[1 + \frac{b_1 2^{n_1}}{(n_1+1)} + \frac{b_2}{(n_2+1)}\right], \quad (4)$$

$$\sigma_{mt} = \sigma_{el} - \frac{4\pi a_0 b_1 n_1 2^{n_1}}{(n_1+1)(n_1+2)}, \quad (5)$$

$$\frac{d\sigma(0°)}{d\Omega} = a_0 + b_1 2^{n_1} + b_2, \quad (6)$$

Table XIV. Angular dependence of the elastic scattering. Approximate values for the vibrationally elastic angle resolved cross sections for CF_4 at 0°, 90° and 180°.

E_0 (eV)	$\frac{d\sigma(0°)}{d\Omega}$ (Å^2/str)	$\frac{d\sigma(90°)}{d\Omega}$ (Å^2/str)	$\frac{d\sigma(180°)}{d\Omega}$ (Å^2/str)
1	(0.2)	(0.5)	(0.3)
2	0.01	0.8	0.1
5	0.6	0.5	0.3
	(1.0)	(0.5)	(0.2)
10	(5.7)	(0.9)	(0.5)
15	(8.0)	(1.0)	(0.5)
20	10.0	1.0	4.0
100	300.0	0.1	0.6

$$\frac{d\sigma(90°)}{d\Omega} = a_0\left[1 + b_1\right] \quad (7)$$

and

$$\frac{d\sigma(180°)}{d\Omega} = a_0\left[1 + b_2\right] \quad (8)$$

Note that it has been assumed that n_1 and n_2 are real numbers with n_2 constrained to be an even integer. These equations can be solved in terms of the experimentally measured quantities but it appears best to use a least squares adjustment procedure involving all equations simultaneously with assumed fixed trial integer values for n_1 and n_2, the latter being an even integer.

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