Summary of single and double electron capture cross sections for ion-atom collisions at low and intermediate energy

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Abstract: As the low energy ion facilities are being constructed there is an urgent need for electron capture cross sections data to be collected. In this report current experimental data, empirical predictions and theoretical models of electron capture cross sections will be presented. Experimental data from various articles will be given in The Appendix.

1. Motivation

One of the most important processes that occurs in collisions between highly charged ions (HCI) and atoms or molecules at low velocity is the electron capture or charge transfer. Information on electron capture cross sections of various multiply charged ions in the collisions with different targets at low and intermediate energy is needed for the construction of low energy ions facilities such as HITRAP at GSI, Darmstadt and a differentially pumped gas cell that is being constructed at the Institute of Physics, Jagiellonian University, Cracow.

Charge exchange between ions and atoms or molecules determines the ion beam lifetime in ion storage rings and ion beam lines. Knowledge on the cross sections for those processes is necessary to predict suitable vacuum conditions in the beam line, in order to minimize the charge loss and, consequently, lengthen the ion beam lifetime.

Calculations of target gas density, which are necessary for avoiding multiple collisions in the target volume, also require information about capture cross sections.

In this report current experimental data as well as empirical approximations of electron capture cross sections will be presented.

2. Experimental data results for single and double electron capture cross sections

Most of the experiments concerning electron capture processes were performed in the seventies and the early eighties. Those experiments focused on ion - H and ion - H_2 interactions, there are only few papers regarding other target atoms, such as He [1] and only recently experiments with Ar or Xe targets were performed [2]. A large amount of data involves single electron capture processes [3-8] but there are also some papers giving double electron capture cross sections values [1, 2, 9-11]. Triple electron capture for Xe^{q+}+Xe $20 \leq q \leq 32$ is given in [12].

Data from all the papers mentioned above is presented in the Appendix with a short description of experiment parameters (i.e. ions charges, species and energies, target used). There is a variety of ion species given, from hydrogen up to zinc, with different charge states – from highly charged to bare ions for light elements ($Z \leq 8$) but only singly and doubly ionized heavy elements. For the energies presented here (0,01 keV to 15 MeV) the cross sections range 10^{-16}-10^{-14} cm^2. A strong energy dependence can be observed for low energy ions, for example in [3] cross sections for the lowest energies are about two orders of magnitude higher than for the fastest ions concerned in that paper.

In the low energy regime electron capture processes are strongly state selective. This case is presented in [12] where strong ion energy dependence is visible for final electron state. This is especially visible for C^{4+} electron capture to 3p state in comparison to capture into 3s or 3d states.

Charge dependence for single electron capture cross sections in low energy regime is also visible [4, 5, 9, and 11].

3. Theoretical calculations and empirical predictions of electron capture cross sections

Electron capture processes for low energy ion-atom collisions are still not very well understood, especially multiple electron capture processes. But there are many empirical predictions as well as theoretical calculations regarding this problem given by different authors. Some of the models are presented in this section.

One of the first empirical formula was given by Salzborn and Müller [13]. They investigated electron capture cross sections for Ne, Ar, Kr and Xe ions collisions with rare gas atoms and molecular gases (H_2, O_2, N_2, CH_4, CO_2) in the energy range from few keV to 100 keV. Following Olson and Salop they assumed that electron capture cross sections in low energy regime do not depend significantly on the projectile energy and for ion charges q>4 do not depend on ion species and should depend only on the initial ion charge state. They used a simple function of initial charge state and ionisation potential:

$$\sigma_{i,i-k} = A_k i^{\alpha_k} I^{\beta_k}$$

where k is the number of electrons captured and A_k, α_k and β_k are the fitting parameters, which strongly depend on the number of electrons captured. (Table1).

Table 1
Salzborn-Muller formula fitting parameters.

k	A_k	α_k	β_k
1	$1{,}43\pm0{,}76\cdot10^{-12}$	$1{,}17\pm0{,}09$	$-2{,}76\pm0{,}19$
2	$1{,}08\pm0{,}95\cdot10^{-12}$	$0{,}71\pm0{,}14$	$-2{,}80\pm0{,}32$
3	$5{,}50\pm5{,}8\cdot10^{-14}$	$2{,}10\pm0{,}24$	$-2{,}89\pm0{,}39$
4	$3{,}57\pm8{,}9\cdot10^{-16}$	$4{,}20\pm0{,}79$	$-3{,}03\pm0{,}86$

Another empirical formula was given by Schlachter at al. in [14]. They used reduced values of cross section and projectile energy per nucleon given by the following equations:

$$\bar{\sigma} = \frac{\sigma Z_2^{1,8}}{q^{0,5}}$$

$$\bar{E} = \frac{E}{Z_2^{1,25} q^{0,7}}$$

where q is the projectile initial charge state, Z_2 is the target atomic number, with σ in cm^2 and energy in keV/u.

Fitting function is given in [14] and the best fitting to the data they present is:

$$\overline{\sigma} = \frac{1{,}1 \cdot 10^{-8}}{\overline{E}^{4,8}} \left[1 - \exp\left(-0{,}037 \cdot \overline{E}^{2,2}\right)\right] \cdot \left[1 - \exp\left(-2{,}24 \cdot 10^{-5} \cdot \overline{E}^{2,6}\right)\right]$$

This estimation of cross section works only if some strictly specified conditions are fulfilled: $10 \leq \overline{E}$ and $q \geq 3$, which mean that this formula does not work well for single and double electron capture nor for collisions in low energy regime.

The simplest model describing electron capture processes in low energy ion –atom collisions is Classical Over-Barrier Model (CBM) which was widely described by many authors, for example [16].

Here the cross section can be expressed as $\sigma=0{,}5\pi R_C^2$, where R_C is the inter-nuclear distance given by [15]:

$$R_C = \frac{2{,}72\left(2\sqrt{q} + 1\right)}{I_P}$$

where I_P is the projectile ionisation potential and q is the ion initial charge state.

4. Summary

In this paper a summary of cross sections for electron capture processes was presented and a brief description of empirical and theoretical calculations was given. Experimental cross sections for various species of ions and atoms are presented in the Appendix.

5. References

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APPENDIX: Summary of single and double electron capture cross sections for ion-atom collisions at low and medium energy

T. V. Goffe, M. B. Shah and H. B. Gilbody, J. Phys. B 12 (1979) 3763:

Single electron capture $\sigma_{q,q-1}$ and loss $\sigma_{q,q+1}$ cross sections by boron ions ranging from singly ionized to bare ions. Measurements carried out for energy range 100-2500 keV for H and H_2 targets.

Energy (keV)	σ_{54} (10^{-16} cm^2)		σ_{43} (10^{-16} cm^2)		σ_{32} (10^{-16} cm^2)		σ_{21} (10^{-16} cm^2)		σ_{10} (10^{-16} cm^2)		σ_{12} (10^{-16} cm^2)		σ_{23} (10^{-16} cm^2)	
	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2
110							11·0	10·7	6·7	6·1	0·57	0·60		
							2·0	1·6	1·0	0·7	0·16	0·16		
185			30·3	18·3	22·5	14·0	11·2	10·6	6·2	5·5	0·78	0·60		
			5·4	2·7	8·0	4·5	1·8	1·4	0·7	0·6	0·13	0·12		
300			25·8	20·2	17·1	12·5	8·9	8·7	4·1	4·1	0·88	0·81		
			3·9	2·6	2·9	1·5	1·2	0·9	0·4	0·4	0·14	0·12		
500			15·7	14·3	9·9	9·5	4·5	5·5	2·2	2·7	0·96	1·18	0·19	0·19
			2·5	1·5	1·2	0·9	0·5	0·5	0·3	±0·2	±0·13	±0·16	±0·03	±0·04
750	10·0	10·0	8·5	10·4	4·3	6·5	2·0	3·8	0·93	1·27	0·92	1·12	0·24	0·24
	±1·9	±2·4	±1·0	±1·0	±0·3	±0·7	±0·2	±0·3	±0·12	±0·09	±0·15	±0·16	±0·03	±0·03
1000	7·1	7·9	4·2	6·3	2·1	3·8	0·90	1·72	0·29	0·60	0·72	1·23	0·23	0·31
	±1·2	±1·0	±0·5	±0·6	±0·2	±0·3	±0·10	±0·10	±0·05	±0·06	±0·11	±0·18	±0·03	±0·04
1250	3·6	5·5	1·90	4·0	1·02	2·22	0·43	0·96	0·16	0·29	0·73	0·90	0·24	0·33
	±0·4	±0·5	±0·30	±0·5	±0·10	±0·15	±0·08	±0·08	±0·02	±0·04	±0·11	±0·12	±0·03	±0·04
1600	1·63	3·23	0·99	2·24	0·41	1·17	0·20	0·48	0·08	0·16	0·53	0·92	0·23	0·39
	±0·20	±0·30	±0·15	±0·24	±0·06	±0·07	±0·04	±0·05	±0·02	±0·02	±0·09	±0·11	±0·03	±0·04
2100	0·60	1·43	0·35	0·98	0·154	0·46	0·073	0·173			0·52	0·87	0·21	0·37
	±0·09	±0·13	±0·07	±0·10	±0·02	±0·04	±0·014	±0·025			±0·10	±0·11	±0·03	±0·04
2500	0·35	0·84	0·20	0·71	0·075	0·26							0·20	0·36
	±0·06	±0·08	±0·05	±0·10	±0·011	±0·02							±0·03	±0·04

Single electron capture and loss cross sections by carbon ions ranging from singly ionized to bare ions. Energy range: 100-2500 keV for H and H_2 targets.

Energy (keV)	σ_{65} (10^{-16} cm^2)		σ_{54} (10^{-16} cm^2)		σ_{43} (10^{-16} cm^2)		σ_{32} (10^{-16} cm^2)		σ_{21} (10^{-16} cm^2)		σ_{10} (10^{-16} cm^2)		σ_{12} (10^{-16} cm^2)		σ_{23} (10^{-17} cm^2)		σ_{34} (10^{-18} cm^2)	
	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2
100									6·6	9·7	7·3	7·8	0·64	0·74				
									±0·6	±0·6	±0·8	±0·8	±0·10	±0·10				
130					27·0	19·0												
					±4·0	±3·0												
148							22·0	14·0										
							±2·0	±1·0										
171					27·0	18·0												
					±4·0	±2·0												
185									5·2	8·0	5·3	5·9	1·05	0·96				
									±0·7	±0·7	±0·5	±0·6	±0·18	±0·09				
220															0·85	0·75		
															±0·18	±0·09		
240							17·0	16·0										
							±2·0	±1·0										
285			33·0	24·0	26·0	17·0			7·0	7·1	3·7	4·2	1·14	1·05	1·49	0·94		
			±7·0	±4·0	±3·0	±2·0			±0·7	±0·5	±0·4	±0·5	±0·18	±0·09	±0·18	±0·18		
375							16·0	14·0	6·1	6·5	2·9	3·6	1·23	1·14	2·4	1·50	1·84	0·47
							±2·0	±1·0	±0·7	±0·6	±0·4	±0·4	±0·18	±0·09	±0·4	±0·18	±0·35	±0·09
507			22·0	19·0	17·0	14·0	11·0	10·0	4·0	4·7	1·8	2·2	1·14	1·23	3·3	2·0	3·4	1·14
			±4·0	±4·0	±2·0	±2·0	±1·0	±1·0	±0·4	±0·3	±0·2	±0·2	±0·18	±0·18	±0·4	±0·3	±0·4	±0·18
707			15·0	15·0	10·5	10·0	5·8	7·3	2·0	2·8	0·90	1·2	1·14	1·40	3·5	3·0	6·0	3·3
			±3·0	±2·0	±1·3	±1·0	±0·4	±0·5	±0·2	±0·2	±0·07	±0·1	±0·15	±0·18	±0·4	±0·3	±0·8	±0·4
860			11·5	13·0	7·0	8·6	3·5	5·0	1·2	2·0	0·68	1·1	1·05	1·50	3·6	3·9		
			±2·0	±2·0	±0·8	±0·8	±0·3	±0·4	±0·1	±0·2	±0·07	±0·1	±0·09	±0·18	±0·5	±0·4		
1100			6·0	8·7	3·6	5·6	1·8	3·3	0·61	1·3	0·37	0·62	0·94	1·44	3·7	4·7	8·8	8·5
			±0·7	±0·7	±0·4	±0·6	±0·2	±0·3	±0·06	±0·1	±0·04	±0·07	±0·09	±0·18	±0·5	±0·5	±0·9	±0·9
1380	4·7	7·4	2·9	5·4	1·8	3·6	0·85	1·9	0·28	0·76	0·21	0·39	0·86	1·36			8·8	9·6
	±0·9	±1·0	±0·2	±0·3	±0·2	±0·4	±0·09	±0·2	±0·03	±0·08	±0·03	±0·05	±0·09	±0·18			±0·9	±0·9
1750	2·5	5·1	1·7	3·5	0·86	2·0	0·41	1·0	0·18	0·41	0·11	0·19	0·76	1·24	3·6	5·5	7·8	12·3
	±0·4	±0·8	±0·2	±0·3	±0·1	±0·2	±0·06	±0·1	±0·02	±0·05	±0·02	±0·03	±0·10	±0·15	±0·5	±0·4	±0·9	±0·9
2100	1·4	3·3	0·76	1·8	0·50	1·2	0·27	0·71	0·098	0·24					3·3	5·4	8·8	14·0
	±0·2	±0·3	±0·1	±0·1	±0·08	±0·1	±0·04	±0·06	±0·015	±0·03					±0·5	±0·4	±1·8	±0·9
2500	0·75	2·0	0·40	1·0														
	±0·1	±0·2	±0·06	±0·1														

G. Lubinski, et al. J. Phys. B 33 (2000) 5275:

State selective electron capture cross section for molecular hydrogen target are presented, for He-like C^{4+}, N^{5+} and O^{6+} ions at the energy range 5-4000 eV/u.

C^{4+}:

E (eV amu^{-1})	3s (10^{-16} cm^2)	3p (10^{-16} cm^2)	3d (10^{-16} cm^2)
5	8.4 ± 1.1	35.1 ± 1.9	1.8 ± 0.8
10	10.7 ± 1.1	37.8 ± 2.0	1.9 ± 0.8
15	12.5 ± 1.4	41.6 ± 2.2	2.3 ± 1.0
25	11.7 ± 1.1	32.0 ± 1.7	1.9 ± 0.7
48	13.7 ± 1.1	30.1 ± 1.6	2.0 ± 0.7
70	16.0 ± 1.1	24.4 ± 1.3	2.1 ± 0.7
100	14.3 ± 1.0	19.6 ± 1.1	1.5 ± 0.5
200	20.5 ± 1.2	21.0 ± 1.1	1.9 ± 0.5
300	19.3 ± 1.2	16.7 ± 0.9	3.4 ± 0.5
400	18.7 ± 1.1	13.3 ± 0.8	3.9 ± 0.5
600	20.7 ± 1.2	9.7 ± 0.7	5.1 ± 0.6
830	16.5 ± 1.0	7.5 ± 0.5	4.9 ± 0.5
1167	15.9 ± 1.4	7.1 ± 0.6	4.7 ± 0.6

N^{5+}:

E (eV amu^{-1})	3s (10^{-16} cm^2)	3p (10^{-16} cm^2)	3d (10^{-16} cm^2)
7	2.0 ± 0.2	0.4 ± 0.2	0.4 ± 0.2
10	2.4 ± 0.2	0.5 ± 0.2	0.4 ± 0.2
16	1.7 ± 0.1	0.6 ± 0.1	0.4 ± 0.1
21	1.2 ± 0.1	0.6 ± 0.1	0.3 ± 0.1
26	1.3 ± 0.1	0.8 ± 0.1	0.2 ± 0.1
38	1.6 ± 0.1	0.9 ± 0.1	0.4 ± 0.1
56	1.7 ± 0.1	1.0 ± 0.1	0.4 ± 0.1
84	1.6 ± 0.1	1.3 ± 0.1	0.5 ± 0.1
101	1.0 ± 0.1	1.1 ± 0.1	0.4 ± 0.1
156	0.8 ± 0.1	1.1 ± 0.1	0.6 ± 0.1
216	0.4 ± 0.1	0.5 ± 0.1	0.6 ± 0.1
307	0.4 ± 0.1	0.5 ± 0.1	0.9 ± 0.1
400	0.4 ± 0.1	0.9 ± 0.1	1.2 ± 0.1
600	0.5 ± 0.2	1.4 ± 0.2	2.0 ± 0.2
700	0.7 ± 0.2	2.1 ± 0.3	2.8 ± 0.3
929	0.8 ± 0.2	3.0 ± 0.2	3.4 ± 0.2
1000	0.7 ± 0.1	3.3 ± 0.2	3.1 ± 0.2
1190	1.0 ± 0.1	4.2 ± 0.2	3.4 ± 0.2
2000	1.4 ± 0.2	6.4 ± 0.3	3.6 ± 0.2
4000	1.9 ± 0.2	6.0 ± 0.3	5.6 ± 0.3

O^{6+}:

E (eV amu^{-1})	4s (10^{-16} cm^2)	4p (10^{-16} cm^2)	4d (10^{-16} cm^2)	4f (10^{-16} cm^2)
7	2.4 ± 1.3	17.9 ± 2.5	0.4 ± 0.4	0.2 ± 0.2
15	2.5 ± 1.2	21.7 ± 2.8	0.6 ± 0.4	0.2 ± 0.2
20	3.7 ± 1.1	25.2 ± 2.5	0.7 ± 0.3	0.3 ± 0.1
32	4.0 ± 1.7	32.4 ± 2.4	0.8 ± 0.5	0.4 ± 0.3
50	5.6 ± 1.6	31.8 ± 2.6	1.0 ± 0.5	1.1 ± 0.6
70	8.7 ± 2.7	31.7 ± 2.4	1.3 ± 0.5	2.4 ± 1.1
100	9.8 ± 1.7	27.8 ± 2.3	1.5 ± 0.5	3.9 ± 1.4
150	11.7 ± 2.1	21.6 ± 2.0	2.2 ± 0.5	4.0 ± 2.0
250	13.9 ± 1.9	15.0 ± 2.1	2.8 ± 0.4	5.9 ± 1.1
350	12.3 ± 2.2	13.9 ± 1.8	3.1 ± 0.7	6.7 ± 1.5
560	14.3 ± 2.1	10.7 ± 1.8	3.1 ± 0.6	5.8 ± 1.3
750	12.3 ± 1.6	9.2 ± 1.7	3.2 ± 0.6	8.0 ± 1.6
980	9.4 ± 1.7	7.9 ± 1.7	3.0 ± 0.5	7.9 ± 1.6
1313	10.0 ± 2.1	8.4 ± 1.8	4.2 ± 0.6	6.5 ± 1.1

R. A. Phaneuf, et al., Phys. Rev. A 26 (1982) 1892:
Total electron capture cross section for O^{+q}, 2≤q≤6 interactions with atomic and molecular hydrogen in the energy range 0,01-10 keV/u.

Ion	Energy (eV/amu)	Velocity (10^7 cm/s)	$\sigma_{q,q-1}$(H)	Standard deviation (10^{-16} cm^2)	Absolute uncertainty	$\sigma_{q,q-1}$(H_2)	Standard deviation (10^{-16} cm^2)	Absolute uncertainty
O^{2+}	188	1.90	4.1	0.3	0.8	1.2	0.3	0.6
	375	2.69	2.5	0.2	0.5	1.8	0.1	0.3
	656	3.56	1.9	0.1	0.3	2.2	0.2	0.5
	1255	4.92	2.2	0.1	0.4	2.9	0.1	0.4
	1885	6.04	2.0	0.1	0.3	3.1	0.1	0.5
	2520	6.98	2.3	0.1	0.4	3.8	0.1	0.6
	3275	7.95	3.3	0.3	0.7	3.9	0.1	0.6
O^{3+}	42	0.90	29.8	5.6	11.6			
	61	1.08				23.7	1.3	5.2
	73	1.19	34.6	6.0	12.7			
	193	1.93	31.7	4.2	10.0	20.9	2.2	5.6
	281	2.33	23.2	0.7	3.4	9.4	0.4	1.5
	363	2.65				7.7	3.2	5.7
	563	3.30	25.3	3.6	8.0	8.3	0.2	1.2
	983	4.35	26.7	0.6	3.8	8.6	0.3	1.3
	1890	6.03	23.7	0.4	3.3	9.6	0.4	1.5
	2830	7.39	22.6	0.5	3.2	9.9	0.3	1.5
	3770	8.53	21.8	0.5	3.1	11.3	0.5	1.8
	4915	9.74	22.4	1.3	4.0	11.7	0.6	2.0
O^{4+}	56	1.04	25.3	5.0	10.2			
	81	1.25				41.0	3.5	10.1
	98	1.37	33.9	3.8	9.9			
	128	1.57	39.6	3.5	10.5	38.0	3.1	9.2
	215	2.04	30.5	3.2	8.6			
	257	2.23	26.6	3.7	8.6	39.6	6.4	13.5
	323	2.49				35.1	3.6	9.3
	375	2.69	23.3	0.9	3.6	25.5	0.4	3.5
	484	3.05				35.8	3.3	9.1
	750	3.80	26.3	0.8	3.9	27.0	0.8	4.0
	1310	5.03	28.3	1.2	4.5	32.2	0.7	4.6
	2515	6.97	26.9	1.4	4.6	29.8	0.9	4.4
	3775	8.53	24.4	1.0	3.9	28.4	0.7	4.1
	5050	9.87	24.5	0.3	3.4	26.2	0.7	3.8
	6575	11.26	23.3	0.7	3.4	25.5	0.3	3.5
O^{5+}	69	1.16	64.1	3.3	15.2			
	100	1.39	71.8	6.8	19.6	18.5	3.9	7.6
	122	1.53	64.0	5.0	16.4			
	160	1.76	55.8	5.8	15.7	22.4	4.6	9.0
	219	2.06	57.7	4.5	14.8			
	269	2.28	37.7	3.4	10.1			
	320	2.48	32.5	2.8	8.6	18.8	5.5	10.1
	403	2.79				19.5	2.6	5.9
	605	3.41				23.1	4.1	8.4
	938	4.25	35.8	0.8	5.1	16.8	0.4	2.4
	1630	5.61	33.8	0.4	4.6	19.6	0.4	2.8
	3135	7.78	34.5	4.5	10.1	22.0	0.8	3.4
	4720	9.54	33.6	1.1	5.0	22.7	0.5	3.2
	6310	11.04	34.5	1.7	5.8	23.2	0.4	3.2
	8205	12.58	33.5	1.3	5.2	25.7	1.2	4.2

O^{6+}	83	1.27	25.0	2.5	7.0			
	120	1.52	27.0	2.4	7.2	52.4	2.9	11.6
	145	1.67				55.1	4.0	12.9
	169	1.81				50.4	7.0	15.6
	192	1.92	36.5	2.9	9.4	51.2	5.2	13.5
	264	2.26	36.7	2.3	9.0	49.1	1.6	10.2
	323	2.50	42.1	2.0	9.9			
	383	2.72	36.5	4.1	10.6			
	484	3.05				51.8	4.5	12.9
	726	3.74				47.9	2.8	10.7
	1125	4.66	31.1	1.5	5.2	41.4	1.4	6.3
	1975	6.17	37.0	0.8	5.2	39.8	0.5	5.5
	3760	8.52	37.9	2.0	6.5	38.6	1.0	5.6
	5675	10.46	39.7	2.6	7.5	37.0	1.2	5.5
	7540	12.06	40.2	1.1	5.9	37.2	0.4	5.1
	9860	13.80	41.8	0.5	5.7	37.7	0.9	5.4

Total electron capture cross section for C^{+q}, $3 \le q \le 6$ interactions with atomic and molecular hydrogen in the energy range 0,01-10 keV/u:

Ion	Energy (eV/amu)	Velocity (10^7 cm/s)	$\sigma_{q,q-1}$(H)	Standard deviation (10^{-16} cm^2)	Absolute uncertainty	$\sigma_{q,q-1}$(H_2)	Standard deviation (10^{-16} cm^2)	Absolute uncertainty
C^{3+}	11	0.46	14.7	2.0	4.7	8.0	2.1	3.9
	20	0.62	10.0	1.2	3.1	9.4	0.7	2.2
	36	0.84	8.5	1.2	2.7			
	39	0.87				13.1	1.5	3.7
	43	0.91	7.5	0.7	2.0			
	57	1.04				11.6	1.1	3.0
	70	1.16	6.8	0.9	2.1	10.2	1.0	2.7
	112	1.47	6.2	1.6	3.0	9.0	1.2	2.7
	161	1.76				5.6	1.6	2.9
C^{4+}	15	0.54	13.7	3.2	6.3			
	27	0.72	17.0	2.9	6.3	53.2	4.9	13.5
	50	0.98	22.8	2.3	6.3	55.6	4.5	13.5
	57	1.05	20.9	1.6	5.4			
	75	1.20				44.5	1.7	9.4
	93	1.34	23.2	1.0	5.4	43.6	0.5	8.8
	150	1.70	25.0	1.1	5.5	37.3	2.8	8.8
	214	2.03	21.2	1.3	5.2	35.6	0.9	7.3
	387	2.73	32.7	1.9	7.9	39.1	2.3	8.7
C^{5+}	71	1.17	24.9	3.7	8.4			
	94	1.35				20.4	0.9	4.4
	115	1.49	24.4	2.1	6.5	21.6	2.7	6.3
	186	1.90	20.3	2.4	6.1	14.5	1.7	4.1
	268	2.27	22.1	1.7	5.7	8.5	0.5	1.9
	2490	6.93	27.2	0.8	4.0	17.9	0.5	2.6
	4280	9.09	31.2	1.3	4.9	23.5	0.8	3.6
	8750	12.99	36.4	1.0	5.3	28.8	0.4	4.0
C^{6+}	142	1.66	7.0	3.8	5.6	34.1	4.3	10.0
	160	1.74	11.8	2.6	5.1	38.4	4.4	10.7
	221	2.06	17.8	3.2	6.3			
	319	2.47	30.7	3.2	8.7	48.0	5.7	13.6

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Single electron capture cross sections for Ne^{+q} $2 \le q \le 7$ from atomic and molecular hydrogen target in the energy range 50-3000 qeV. Cross sections $\sigma_{q,q-1}$ are given in $10^{-15} cm^2$

E (eV/q)	$\sigma_{2,1}^{(Ne)}(H)$	$\sigma_{3,2}^{(Ne)}(H)$	$\sigma_{4,3}^{(Ne)}(H)$	$\sigma_{5,4}^{(Ne)}(H)$	$\sigma_{6,5}^{(Ne)}(H)$	$\sigma_{7,6}^{(Ne)}(H)$
400	0.045±0.007	1.37±0.12	1.77±0.16	2.70±0.31	1.32±0.36	
600	0.033±0.005	1.55±0.12	1.42±0.14	3.19±0.36	1.27±0.71	
800	0.038±0.017	1.16±0.38	1.29±0.43	2.56±0.65	1.33±0.54	3.15±1.1
1000	0.035±0.006	1.27±0.15	1.49±0.18	2.00±0.22	1.98±0.36	

E (eV/q)	$\sigma_{2,1}^{(Ne)}(H_2)$	$\sigma_{3,2}^{(Ne)}(H_2)$	$\sigma_{4,3}^{(Ne)}(H_2)$	$\sigma_{5,4}^{(Ne)}(H_2)$	$\sigma_{6,5}^{(Ne)}(H_2)$	$\sigma_{7,6}^{(Ne)}(H_2)$
200	0.081±0.004	2.33±0.03	3.66±0.07	3.93±0.15	4.49±0.45	
400	0.114±0.005	2.45±0.04	3.21±0.07	3.67±0.16	3.76±0.40	1.86±0.42
600	0.128±0.005	2.64±0.04	3.20±0.07	3.60±0.16	3.70±0.42	
800	0.121±0.005	2.50±0.04	2.87±0.06	3.20±0.013	3.42±0.26	4.04±0.40
1000	0.117±0.005	2.48±0.03	2.98±0.06	2.74±0.12	4.95±0.43	

Double electron capture cross sections for Ne^{+q} from molecular hydrogen target in the energy range 50-3000 qeV. Cross sections $\sigma_{q,q-2}$ are given in $10^{-15} cm^2$

E (eV/q)	$\sigma_{4,2}^{(Ne)}(H_2)$	$\sigma_{5,3}^{(Ne)}(H_2)$
200	0.084±0.007	0.17±0.03
400	0.069±0.007	0.21±0.04
600	0.097±0.01	
800	0.082±0.08	0.15±0.04
1000	0.069±0.07	

Single electron capture cross sections for Ar^{+q} $2 \le q \le 10$ from atomic and molecular hydrogen target in the energy range 50-3000 qeV. Cross sections $\sigma_{q,q-1}$ are given in $10^{-15} cm^2$

E (eV/q)	$\sigma_{2,1}^{(Ar)}(H)$	$\sigma_{3,2}^{(Ar)}(H)$	$\sigma_{4,3}^{(Ar)}(H)$	$\sigma_{5,4}^{(Ar)}(H)$	$\sigma_{6,5}^{(Ar)}(H)$	$\sigma_{7,6}^{(Ar)}(H)$	$\sigma_{8,7}^{(Ar)}(H)$	$\sigma_{9,8}^{(Ar)}(H)$	$\sigma_{10,9}^{(Ar)}(H)$
200	0.029±0.014	1.77±0.24	1.92±0.33	2.61±0.40	3.74±0.67	3.83±0.78	2.95±0.68	3.30±1.0	4.48±1.76
520	0.034±0.012	1.48±0.14	1.62±0.20	2.24±0.29	2.90±0.39	2.70±0.41	2.51±0.45	3.63±0.72	1.09±0.48
800	0.044±0.014	1.53±0.16	1.37±0.19	2.37±0.34	2.87±0.48	2.00±0.42	2.48±0.49	2.29±0.56	3.21±1.19
1250	0.052±0.015	1.48±0.26	1.60±0.25	1.84±0.29	2.66±0.43	3.11±0.53	2.52±0.52	4.67±0.97	2.28±1.14

E (eV/q)	$\sigma_{2,1}^{(Ar)}(H_2)$	$\sigma_{3,2}^{(Ar)}(H_2)$	$\sigma_{4,3}^{(Ar)}(H_2)$	$\sigma_{5,4}^{(Ar)}(H_2)$	$\sigma_{6,5}^{(Ar)}(H_2)$	$\sigma_{7,6}^{(Ar)}(H_2)$	$\sigma_{8,7}^{(Ar)}(H_2)$	$\sigma_{9,8}^{(Ar)}(H_2)$	$\sigma_{10,9}^{(Ar)}(H_2)$
50	0.110±0.006	2.24±0.05	2.93±0.11	2.43±0.12	4.27±0.22	4.10±0.27			
100	0.166±0.009	2.41±0.06	2.86±0.11	3.01±0.15	5.20±0.27	5.50±0.34			
200	0.242±0.007	1.83±0.03	2.87±0.07	2.77±0.11	5.05±0.19	6.17±0.26	4.54±0.25	7.24±0.50	5.40±0.74
520	0.279±0.007	1.62±0.03	2.88±0.07	2.62±0.11	4.20±0.18	5.23±0.25	4.89±0.29	6.53±0.49	3.76±0.62
800	0.244±0.007	1.53±0.03	2.78±0.08	2.82±0.12	5.12±0.20	5.12±0.25	4.59±0.28	4.87±0.41	6.04±0.81
1250	0.266±0.008	1.53±0.03	3.14±0.10	2.92±0.14	4.29±0.21	5.56±0.29	5.25±0.32	7.53±0.55	7.59±0.91
2000	0.282±0.008	1.30±0.03	3.01±0.08	2.61±0.12	4.39±0.20	5.57±0.27	4.81±0.28	5.63±0.46	5.97±0.73
3000	0.258±0.007	1.26±0.03	2.92±0.09	2.71±0.13	4.19±0.21	4.94±0.26	4.74±0.32	5.56±0.49	4.89±0.72

Double electron capture cross sections for Ar^{+q} from molecular hydrogen target in the energy range 50-3000 qeV. Cross sections $\sigma_{q,q-2}$ are given in $10^{-15} cm^2$

E (eV/q)	$\sigma_{4,2}^{(Ar)}(H_2)$	$\sigma_{5,3}^{(Ar)}(H_2)$	$\sigma_{6,4}^{(Ar)}(H_2)$	$\sigma_{7,5}^{(Ar)}(H_2)$
100	0.59±0.04			
200	0.74±0.03		0.18±0.02	0.17±0.02
520	0.62±0.03	0.71±0.05	0.41±0.05	0.26±0.03
800	0.62±0.03	0.79±0.05	0.36±0.04	0.22±0.03
1250	0.55±0.03			0.22±0.03
2000	0.59±0.03	0.55±0.04	0.29±0.04	0.12±0.02
3000	0.56±0.03		0.31±0.04	0.17±0.03

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Cross sections for charge exchange processes of Br^{q+} and I^{q+} ions collisions with H_2 and He at the energy 6-15 MeV. σ the values are given in 10^{-16} cm^2/molecule and relative errors δσ/σ are in percent:

TABLE III. Charge-changing cross sections σ(q, q+n) in 10^{-16} cm^2/molecule and relative errors δσ/σ in percent.

Ion	Energy (MeV)	Target	n \ q	2+		3+		4+		5+		6+		7+		8+		9+		10+	
Br	6	He	−1	1.08	4	2.18	4	5.14	3	7.12	3	9.97	3	9.30	3	13.0	3	16.6	3		
			−2			0.033	15	0.159	25	0.392	20	0.684	20	0.740	20	0.310	30	0.250	70		
			1	1.98	4	1.25	5	0.832	5	0.442	6	0.230	10	0.124	10	0.040	40	0.025	60		
			2	0.445	15	0.313	7					0.022	10								
			3	0.160	7																
Br	10	He	−1			0.898	5	1.97	4	3.38	4	5.53	3	5.16	3	7.68	3	10.35	3	13.35	3
			−2							0.056	50	0.104	50	0.154	50	0.086	70	< 0.01		< 0.2	
			1			1.25	5	0.854	6	0.56	5	0.320	10	0.173	15	0.106	20	0.06	20	0.038	50
			2			0.331	7	0.195	10	0.131	10	0.048	10								
Br	14	He	−1					0.738	4	1.39	4	2.74	3	3.14	3	4.45	3	6.11	4	8.18	3
			−2											0.038	20	< 0.001		0.037	60	0.022	99
			1					0.819	4	0.555	5	0.429	5	0.228	6	0.166	8	0.111	25		
			2					0.195	5	0.155	6	0.037	7	0.019	10						
Br	14	H_2	−1					0.640	5	1.22	4	2.66	4	2.74	3	4.19	3				
			−2									0.007	60	0.016	40	0.006	75				
			1					0.740	5	0.45	6	0.286	7	0.162	8	0.118	10				
			2					0.130	7	0.075	8	0.021	15	0.010	15	0.009	15				
			3					0.027	10												
			4					0.004	20												
I	6	He	−1	1.12	5	3.46	4	6.76	4	9.33	4	10.5	3	10.4	3	13.4	3	17.7	3		
			−2					0.057	99	0.273	60	0.418	30	0.811	25	0.640	30	0.910	40		
			1	2.60	4	1.50	5	1.27	6	0.761	7	0.587	8	0.294	9	0.168	15	0.034	50		
			2	0.983	5	0.732	6	0.321	8	0.211	9	0.078	10								
			3	0.492	6	0.239	7	0.110	10												
			4	0.153	7																
I	10	He	−1			1.98	4	4.46	4	6.28	3	7.35	3	7.71	3	10.6	3	13.0	3		
			−2					0.027	60	0.117	30	0.185	40	0.511	25	0.272	35	0.500	35		
			1			1.63	4	1.34	5	0.847	5	0.744	7	0.471	9	0.336	12	0.199	25		
			2			0.717	5	0.463	6	0.349	6	0.194	8	0.124	9						
			3			0.328	6	0.18	10	0.092	7										
I	15	He	−1					2.26	4	3.21	4	4.02	3	5.59	3	7.41	4	9.39	3	12.2	3
			−2									0.044	50	0.240	25	0.063	75	0.163	50	0.282	50
			1					1.24	5	0.906	6	0.837	6	0.545	6	0.452	7	0.386	8	0.258	12
			2					0.483	6	0.437	6	0.278	7								
			3					0.275	7	0.152	8										

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Single electron capture cross sections for He- and Li-like B, C, N, O ions on molecular and atomic hydrogen target for the energy range 4-25 qkeV

Ion	v (10^8 cm/sec)	$\sigma_{q,q-1}(H)$ (10^{-16} cm^2)	$\sigma_{q,q-1}(H_2)$ (10^{-16} cm^2)
B^{2+}	0.43	11.8(2.0)	20.4(0.8)
	0.47	14.2(1.2)	20.3(0.6)
	0.66	18.5(1.2)	17.8(0.4)
	0.73	15.8(1.4)	17.9(0.6)
	0.75	17.4(1.6)	18.4(0.8)
B^{3+}	0.52	3.3(0.6)	5.4(0.3)
	0.57	4.3(0.5)	6.4(0.2)
	0.73	9.3(0.7)	5.0(0.2)
	0.81	8.7(1.1)	8.3(0.3)
	0.92	10.6(0.8)	8.5(0.6)
C^{3+}	0.73	16.3(1.8)	6.4(0.3)
N^{3+}	0.51	20.8(1.2)	6.4(0.5)
	0.58	19.3(0.8)	6.8(0.4)
	0.72	17.7(0.8)	6.8(0.2)
	0.86	18.7(0.8)	7.9(0.3)
	0.99	15.8(1.2)	9.4(0.4)
B^{4+}	0.60	30.9(2.8)	22.1(1.0)
	0.66	26.5(1.6)	22.7(0.6)
	0.94	25.1(2.4)	23.0(0.8)
	1.06	27.2(1.0)	23.3(0.6)
C^{4+}	0.48	28.8(1.4)	26.6(0.6)
	0.58	27.5(2.0)	24.8(1.2)
	0.66	32.7(1.8)	25.9(0.8)
	0.73	29.3(2.6)	23.6(0.8)
	0.84	28.5(2.6)	23.2(1.2)
	0.99	28.2(2.6)	22.4(0.8)
	1.06	27.3(2.2)	21.7(1.0)
N^{4+}	0.44	29.2(1.0)	34.0(0.8)
	0.55	30.5(1.0)	33.8(0.6)
	0.59	26.0(4.8)	29.6(1.4)
	0.64	29.2(0.6)	30.8(0.4)
	0.73	29.5(1.0)	31.4(1.2)
	0.84	26.2(0.8)	27.0(0.4)
	0.99	24.4(0.8)	25.2(0.4)
	1.16	25.0(1.2)	28.1(1.2)
B^{5+}	1.05	22.6(4.0)	22.8(3.4)
C^{5+}	0.82	29.2(9.2)	20.0(1.4)
N^{5+}	0.51	20.3(2.8)	13.0(0.6)
	0.62	25.4(0.6)	18.3(0.3)
	0.67	24.6(1.4)	17.9(1.4)
	0.72	26.7(1.2)	19.7(0.6)
	0.82	27.2(1.4)	22.5(0.4)
	0.94	29.6(1.0)	21.7(0.8)
	1.11	33.1(2.2)	23.2(0.6)
	1.29	30.0(2.6)	26.3(1.0)
O^{5+}	0.56	27.8(3.6)	18.4(0.6)
	0.61	32.7(2.2)	22.0(1.4)
	0.73	34.8(2.0)	22.4(1.0)
	0.87	30.4(2.2)	22.1(0.8)
	0.98	32.4(1.0)	22.8(0.6)
O^{6+}	0.61	31.0(5.4)	35.9(2.8)
	0.67	37.7(6.8)	34.6(4.2)
	0.73	32.0(7.8)	33.9(1.8)
	0.95	37.6(3.8)	34.7(2.8)
	1.08	36.7(2.4)	34.3(1.4)
F^{6+}	0.73	35.5(2.2)	38.8(1.0)
Ar^{3+}	0.70	42.8(8.4)	34.9(1.6)

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Cross sections for one-electron capture by Ba^{2+}, Ti^{2+}, Mg^{2+}, Cd^{2+}, Zn^{2+}, Kr^{2+} and B^{2+} in both H and H_2 have been determined in the energy range 0.8-40 keV.

Energy (keV)	Ba^{2+}		Tl^{2+}		Mg^{2+}		Cd^{2+}		Zn^{2+}		Kr^{2+}		B^{2+}	
	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2	H	H_2
0·8	—	—	—	—	—	—	—	—	4·3 ±0·5	8·7 ±0·6	—	—	—	—
1·0	—	—	—	—	—	—	—	—	5·2 ±0·5	9·0 ±0·6	0·07 ±0·06	2·13 ±0·05	—	—
1·3	—	—	—	—	—	—	—	—	6·4 ±0·5	9·9 ±0·5	—	—	—	—
1·5	—	0·05 ±0·002	—	—	—	—	—	4·95 ±0·2	7·6 ±0·6	10·9 ±0·6	0·14 ±0·08	2·54 ±0·05	—	—
1·8	—	0·07 ±0·004	—	—	—	—	—	—	—	—	—	—	—	—
2·0	—	0·11 ±0·01	—	—	0·025 ±0·005	0·057 ±0·003	20·1 ±1·4	4·4 ±0·1	7·8 ±0·4	10·2 ±0·4	0·24 ±0·06	2·87 ±0·08	—	—
2·3	—	0·15 ±0·01	—	—	—	—	—	—	—	—	—	—	—	—
2·5	—	0·27 ±0·01	—	—	—	—	20·0 ±1·2	4·2 ±0·2	8·6 ±0·6	9·8 ±0·6	—	—	—	—
3·0	—	0·42 ±0·02	—	0·32 ±0·03	0·064 ±0·007	0·068 ±0·005	20·8 ±0·7	4·2 ±0·1	10·5 ±0·4	10·1 ±0·3	0·35 ±0·05	3·15 ±0·08	1·0 ±0·3	22·6 ±1·0
4·0	—	0·74 ±0·02	—	0·38 ±0·02	0·1 ±0·01	0·076 ±0·003	19·5 ±1·2	3·9 ±0·1	10·7 ±0·4	9·3 ±0·3	0·4 ±0·06	3·23 ±0·08	2·3 ±0·5	22·6 ±0·5
5·0	—	0·96 ±0·04	—	0·42 ±0·02	0·15 ±0·01	0·083 ±0·002	19·0 ±0·9	3·5 ±0·1	13·3 ±0·7	9·0 ±0·3	0·5 ±0·06	3·25 ±0·04	4·5 ±0·7	22·7 ±0·3
6·0	—	1·06 ±0·03	—	0·52 ±0·04	0·23 ±0·02	0·091 ±0·005	17·3 ±0·6	3·25 ±0·1	13·7 ±0·7	8·6 ±0·2	0·6 ±0·07	3·32 ±0·08	5·6 ±0·9	21·7 ±0·6
7·0	—	1·16 ±0·03	0·14 ±0·03	0·53 ±0·03	0·34 ±0·02	0·11 ±0·003	18·8 ±0·8	3·3 ±0·1	13·9 ±0·8	7·9 ±0·2	0·7 ±0·07	3·42 ±0·04	6·6 ±0·7	21·9 ±0·6
8·0	—	1·19 ±0·04	0·19 ±0·04	0·53 ±0·03	0·4 ±0·03	0·11 ±0·01	16·7 ±1·0	3·0 ±0·1	15·6 ±0·6	8·3 ±0·2	0·8 ±0·07	3·51 ±0·03	8·2 ±0·7	21·6 ±0·9
9·0	—	1·26 ±0·03	0·29 ±0·05	0·66 ±0·03	0·55 ±0·03	0·12 ±0·01	17·6 ±0·9	2·9 ±0·1	15·6 ±1·0	7·6 ±0·4	0·9 ±0·07	3·53 ±0·03	10·0 ±0·7	21·2 ±0·7
10·0	—	1·22 ±0·07	0·36 ±0·05	0·75 ±0·05	0·71 ±0·05	0·14 ±0·01	16·5 ±0·6	2·8 ±0·04	17·5 ±0·7	7·6 ±0·2	0·95 ±0·07	3·52 ±0·06	11·7 ±0·7	20·6 ±0·5
11·0	—	—	0·43 ±0·08	0·93 ±0·09	—	—	—	—	—	—	— —	—	—	
12·0	—	1·32 ±0·04	0·58 ±0·08	1·02 ±0·06	1·1 ±0·06	0·17 ±0·01	16·8 ±0·6	2·7 ±0·1	16·8 ±0·9	7·2 ±0·2	1·1 ±0·08	3·67 ±0·05	13·5 ±0·7	20·4 ±0·6
13·0	—	—	0·69 ±0·09	0·97 ±0·06	—	—	—	—	—	—	—	—	—	—
14·0	0·07 ±0·02	1·36 ±0·04	0·96 ±0·1	1·1 ±0·1	1·3 ±0·1	0·18 ±0·01	16·2 ±0·6	2·6 ±0·03	17·7 ±0·9	7·0 ±0·3	1·2 ±0·08	3·74 ±0·07	15·1 ±0·9	19·3 ±0·9
16·0	—	—	0·98 ±0·09	1·21 ±0·04	1·7 ±0·07	0·21 ±0·01	—	—	—	—	—	—	—	—
17·5	0·18 ±0·02	1·46 ±0·03	—	—	—	—	17·4 ±0·6	2·6 ±0·03	18·4 ±1·5	6·4 ±0·2	1·4 ±0·08	3·84 ±0·06	16·1 ±0·6	18·7 ±0·5
18·0	—	—	1·24 ±0·08	1·32 ±0·03	2·1 ±0·1	0·25 ±0·01	—	—	—	—	—	—	—	—
20·0	0·32 ±0·02	1·53 ±0·02	1·47 ±0·1	1·35 ±0·03	2·3 ±0·1	0·28 ±0·01	16·3 ±0·8	2·3 ±0·1	19·1 ±1·0	6·6 ±0·1	1·54 ±1·09	4·06 ±0·09	16·2 ±0·8	18·4 ±0·7
22·5	0·4 ±0·03	1·54 ±0·07	1·74 ±0·1	1·43 ±0·02	2·5 ±0·1	0·32 ±0·02	15·8 ±0·9	2·2 ±0·1	18·5 ±1·6	6·1 ±0·2	1·64 ±0·09	3·99 ±0·06	16·7 ±0·8	18·1 ±0·8
25·0	0·47 ±0·04	1·57 ±0·04	2·06 ±0·2	1·57 ±0·03	2·8 ±0·1	0·36 ±0·01	16·9 ±0·9	2·4 ±0·1	16·0 ±0·6	5·9 ±0·1	1·8 ±0·09	4·11 ±0·1	16·6 ±0·7	17·7 ±0·5
27·5	—	—	—	—	3·1 ±0·2	0·39 ±0·01	—	—	—	—	—	—	—	—
30·0	0·64 ±0·05	1·66 ±0·06	2·3 ±0·1	1·73 ±0·03	3·4 ±0·1	0·4 ±0·01	16·6 ±0·7	2·2 ±0·1	16·3 ±1·1	6·1 ±0·1	2·1 ±0·1	4·61 ±0·2	15·7 ±0·6	17·1 ±0·4
35·0	0·73 ±0·04	1·66 ±0·05	2·7 ±0·2	1·81 ±0·07	3·9 ±0·2	0·47 ±0·02	17·2 ±1·1	2·2 ±0·1	16·0 ±0·7	6·1 ±0·1	2·5 ±0·1	5·1 ±0·07	14·8 ±0·7	16·8 ±0·6
40·0	—	—	3·02 ±0·2	1·9 ±0·06	4·3 ±0·2	0·51 ±0·01	—	—	—	—	—	—	—	—

W. L. Nutt, et al.,J. Phys. B 11 (1978) L181
Cross sections for electron capture by C^{2+} and Ti^{2+} ions in H and H_2 have been determined within the energy range 0.5-14 keV

	C^{2+}		Ti^{2+}		
Energy (keV)	$\sigma_{21}(H)$ (10^{-17} cm^2)	$\sigma_{21}(H_2)$ (10^{-17} cm^2)	$\sigma_{21}(H)$ (10^{-17} cm^2)	$\sigma_{21}(H_2)$ (10^{-17} cm^2)	$\sigma_{20}(H_2)$ (10^{-17} cm^2)
0·5	11·0 ± 2·4	33·2 ± 2·1	—	—	—
0·7	16·3 ± 3·9	45·4 ± 4·3	—	—	—
1·0	21·4 ± 5·2	52·2 ± 5·2	—	—	—
1·5	24·1 ± 4·9	54·7 ± 5·0	—	—	—
2·0	37·0 ± 5·5	67·2 ± 5·0	—	—	—
3·0	44·1 ± 6·4	72·3 ± 6·5	—	3·2 ± 0·3	2·7 ± 0·4
4·0	40·9 ± 4·5	70·6 ± 2·6	—	3·8 ± 0·2	3·2 ± 0·5
5·0	44·1 ± 6·9	76·1 ± 5·6	—	4·2 ± 0·2	3·0 ± 0·4
6·0	45·8 ± 6·6	79·7 ± 8·0	—	5·2 ± 0·4	3·3 ± 0·6
7·0	42·3 ± 6·3	73·6 ± 7·9	1·4 ± 0·3	5·3 ± 0·3	3·5 ± 0·7
8·0	—	—	1·9 ± 0·4	5·3 ± 0·3	3·9 ± 0·7
8·5	44·1 ± 6·5	83·3 ± 5·5	—	—	—
9·0	—	—	2·9 ± 0·5	6·6 ± 0·3	3·5 ± 0·7
10·0	42·3 ± 7·9	90·0 ± 7·0	3·6 ± 0·5	7·5 ± 0·5	3·5 ± 0·6
11·0	—	—	4·3 ± 0·8	9·3 ± 0·9	3·1 ± 0·7
12·0	43·5 ± 7·9	90·7 ± 6·5	5·8 ± 0·8	10·2 ± 0·6	2·2 ± 0·5
13·0	—	—	6·9 ± 0·9	9·7 ± 0·6	2·7 ± 0·5
14·0	47·0 ± 8·9	92·1 ± 6·1	9·6 ± 1·1	11·0 ± 1·0	2·2 ± 0·9

K. H. Berkner, et al., Phys. Rev A 23 (1981) 2891
Single and double electron capture cross sections for $Fe^{q+}+H_2$. $3 \le q \le 25$. All the values are given in 10^{-16}cm^2/molecule

Energy (MeV)	keV/amu	Charge state	$\sigma_{q,q-1}$	$\sigma_{q,q-2}$
190 ± 9	3400	25	0.000 39	
		24	0.000 36	
		23	0.000 30[a]	
		22	0.000 28[b]	
		21	0.000 25[a]	
		20	0.000 23[a]	
65.0 ± 1.9	1160	22	0.043 0	0.000 39[a]
		20	0.031 5	0.000 14[b]
		18	0.025 0	0.000 25[a]
		16	0.014 2	0.000 06[d]
		14	0.010 8	
		13		
		12	0.006 4	
		11		
60.0 ± 1.8	1070	21	0.051	0.005[a]
		20	0.045	
16.5 ± 0.7	294	16	5.6[a]	
		15		
		14	4.4	
		13		
		12	2.8	
		11		
		10	1.3	
15.8 ± 0.5	282	9	1.21	
15.4 ± 0.5	275	14	5.70	0.30[c]
		12	3.3	0.16[c]
6.16 ± 0.29	110	3	0.65	
5.77 ± 0.28	103	13	43.6	
		11	31.6	
		9	18.9	
		7	11.3	

[a] ±10% uncertainty.
[b] ±15% uncertainty.
[c] ±20% uncertainty.
[d] ±30% uncertainty.

K. H. Berkner, et al., J. Phys. B 11 (1978) 875

Experimental single-electron-capture cross sections $\sigma_{q,q-1}$ Fe^{q+} + H_2 collisions. All cross sections have an absolute uncertainty of 10% except for the one marked † , for which the uncertainty is 15%. Cross sections (10^{-17} cm^2/molecule)

Energy (MeV amu^{-1})	Incident charge state q	Cross sections (10^{-17} cm^2/molecule)	
		$\sigma_{q,q-1}$	σ_I
1·10	11+		330
	12+	0·064†	355
	13+		385
	14+	0·109	435
	16+	0·142	510
	18+	0·250	630
	20+	0·315	740
	22+	0·430	950
0·277	9+	11·9	485
0·262	12+	32·8	
	14+	57·0	

R. A. Phaneuf, Phys. Rev. A 28 (1983) 1310

Single electron capture cross sections of Fe^{q+} $3 \le q \le 14$ on the H and H_2 target in the energy range 10-95 eV/u

q	Energy eV/amu	Velocity 10^6 cm/s	$\sigma_{q,q-1}$(H)	Random[a] uncertainty (10^{-16} cm^2)	Total[b] uncertainty	$\sigma_{q,q-1}$(H_2)	Random[a] uncertainty (10^{-16} cm^2)	Total[b] uncertainty
3	10.4	4.48	44	±3	±11			
3	20.4	6.27	44	3	11	28	±5	±10
4	13.8	5.16	25	2	6			
4	27.2	7.24	17	4	9	18	4	8
5	17.3	5.78	48	3	10			
5	34.0	8.10	48	3	10	52	5	13
6	20.8	6.33	57	4	13			
6	40.8	8.87	58	7	16	52	5	12
7	24.2	6.83	70	9	20			
7	47.6	9.58	81	4	16	56	6	14
8	27.7	7.31	90	14	28			
8	54.4	10.24	77	8	19	62	5	13
9	61.2	10.87	108	6	20	83	8	19
10	68.0	11.45	117	8	23	80	11	22
11	74.8	12.01	119	11	26	92	14	28
12	81.6	12.55	68	11	22	56	20	36
13	88.4	13.06	112	15	31	105	17	32
14	95.2	13.55	128	23	44			

N. Selberg, Phys. Rev. A 56 (1997) 4626

Absolute charge-exchange cross sections for the interaction between slow Xe^{q+} .15<q<43 projectiles and neutral He, Ar, and Xe for ion energy 3,8 qkeV.

TABLE I. Partial cross sections $\sigma^{r}_{q,q-p}$ for the processes $Xe^{q+} + He \rightarrow He^{(q-p)+} + He^{r+} + (r-p)e^-$ in units of 10^{-15} cm^2. In the cases where only single-electron-capture cross sections ($\sigma^{1}_{q,q-1}$) are given, the results are obtained by means of the double-collision method (cf. Sec. III B). The collision energy was 3.8q keV.

q	$\sigma^{1}_{q,q-1}$	$\sigma^{2}_{q,q-1}$	$\sigma^{2}_{q,q-2}$
30	11.1±1.4		
31	12.6±1.6	3.4±0.5	1.2±0.2
32	9.6±1.2	2.8±0.5	0.9±0.2
33	14.4±1.3	4.1±0.5	1.0±0.2
34	13.6±1.0		
35	13.5±1.3	3.7±0.4	1.0±0.1
36	13.6±1.5	3.2±0.4	1.4±0.2
37	14.2±2.0	3.2±0.5	1.4±0.3
38	11.8±1.4	5.9±0.9	1.6±0.3
39	17.6±3.1		
40	14.4±2.0	3.2±0.6	2.1±0.5
41	17.0±4.9		
42	16.4±3.4	4.6±1.4	2.2±0.8

TABLE II. Same as Table I, but with Ar as a target.

q	$\sigma^{1}_{q,q-1}$	$\sigma^{2}_{q,q-1}$	$\sigma^{3}_{q,q-1}$	$\sigma^{4}_{q,q-1}$	$\sigma^{5}_{q,q-1}$	$\sigma^{6}_{q,q-1}$
24	11.3±1.3					
25	10.9±0.9	5.3±0.5	3.5±0.4	1.2±0.1		
26	13.4±1.8	7.0±1.0	3.7±0.5	1.0±0.2		
27	13.7±1.6	6.6±0.9	4.1±0.4	1.1±0.2	0.4±0.09	
28	13.9±1.3	6.6±0.7	5.4±0.6	2.0±0.3	1.0±0.2	
29	5.9±0.4	3.3±0.3	2.3±0.2	0.8±0.1	0.5±0.06	0.3±0.05
30	15.2±1.4	6.1±0.7	3.7±0.5	1.7±0.3	1.0±0.2	
31	15.3±1.1	5.9±0.5	3.7±0.3	1.7±0.2	0.9±0.1	
32	12.3±1.9	4.5±0.8	2.5±0.4	1.3±0.2		
34	21.6±5.5					
35	18.9±2.1	5.7±1.0	4.8±0.8	1.3±0.4		
36	22.0±4.3					
37	18.6±2.3	5.4±0.9	3.1±0.6	1.2±0.2		
39	14.0±4.4					
40	16.7±2.6	5.4±1.2	1.6±0.5	0.7±0.3		
41	22.6±3.1	7.6±1.7	4.9±1.2	2.4±0.7	1.2±0.4	
42	24.0±4.5					
43	18.6±2.8	5.7±1.0	2.1±0.4	0.8±0.2		

q	$\sigma^{2}_{q,q-2}$	$\sigma^{3}_{q,q-2}$	$\sigma^{4}_{q,q-2}$	$\sigma^{5}_{q,q-2}$	$\sigma^{6}_{q,q-2}$	$\sigma^{7}_{q,q-2}$
25	0.4±0.07	0.8±0.1	1.0±0.1	1.0±0.12		
26	0.4±0.09	1.4±0.2	1.6±0.2			
27	0.2±0.06	0.6±0.1	0.8±0.2	1.4±0.2	1.2±0.2	0.7±0.1
28	0.9±0.2	1.2±0.2	1.1±0.2	1.4±0.2		
29	0.5±0.06	0.8±0.09	0.4±0.05			
30	1.6±0.3	1.9±0.3	1.8±0.3	1.9±0.3		
31	1.4±0.2	2.3±0.2	1.4±0.2	1.3±0.2		
32	1.6±0.3	2.3±0.4	1.1±0.2	1.2±0.2	1.0±0.2	
35	2.6±0.6	2.9±0.6	2.7±0.6	1.5±0.4		
37	2.3±0.5	2.2±0.4	1.6±0.4	1.2±0.3		
40	2.0±0.6	3.4±0.8	2.6±0.7			
41	1.8±0.6	6.0±1.4	2.8±0.8			
43	0.6±0.2	1.9±0.4	2.1±0.4			

TABLE III. Same as Table I, but with Xe as a target.

q	$\sigma^1_{q,q-1}$	$\sigma^2_{q,q-1}$	$\sigma^3_{q,q-1}$	$\sigma^4_{q,q-1}$	$\sigma^5_{q,q-1}$	$\sigma^6_{q,q-1}$
14	9.9±0.4					
15	12.1±0.6	7.2±0.4	3.3±0.2	1.4±0.9		
19	11.9±1.8					
20	14.9±0.7	8.3±0.4	4.6±0.2	2.7±0.2	1.2±0.09	0.2±0.05
24	17.4±1.3					
25	17.5±1.0	8.2±0.5	4.5±0.3	2.6±0.2	1.6±0.2	0.5±0.08
27	25.8±3.2					
28	17.6±0.9	9.4±0.5	5.0±0.3	2.7±0.2	1.6±0.1	0.9±0.08
29	23.1±2.1					
30	20.9±1.2	10.7±0.7	4.7±0.4	2.8±0.2	1.4±0.1	0.6±0.08
31	19.3±2.1	9.1±1.1	4.5±0.6	2.2±0.3		
32	24.4±1.4	11.1±0.9	4.7±0.4	3.2±0.3	1.2±0.2	
34	21.9±3.5					
35	21.3±3.2	8.4±1.4	3.5±0.6	1.6±0.4	1.2±0.3	0.7±0.2
36	25.3±4.5	10.0±1.8	4.8±0.9	2.0±0.4	1.2±0.3	
37	28.8±4.2	12.2±2.0	4.8±0.9	1.6±0.4		

q	$\sigma^2_{q,q-2}$	$\sigma^3_{q,q-2}$	$\sigma^4_{q,q-2}$	$\sigma^5_{q,q-2}$	$\sigma^6_{q,q-2}$	$\sigma^7_{q,q-2}$
15	0.2±0.03	0.4±0.04	0.8±0.06	1.3±0.08	1.0±0.07	
20	0.8±0.1	1.8±0.2	1.8±0.2	1.8±0.2	1.5±0.2	
25	1.3±0.2	1.7±0.2	2.0±0.2	2.0±0.2	1.4±0.2	1.0±0.1
28	0.8±0.08	1.3±0.1	1.5±0.1	1.2±0.09	1.2±0.09	0.7±0.07
30	2.0±0.2	2.8±0.2	2.7±0.2	2.0±0.2	1.6±0.2	0.9±0.09
31	3.1±0.4	3.6±0.4	2.5±0.3	2.4±0.3	2.0±0.3	1.6±0.2
32	4.6±0.4	5.0±0.5	4.8±0.4	3.6±0.4	3.0±0.3	2.0±0.2
35	5.3±0.9	6.3±1.1	4.4±0.8	3.5±0.6	1.6±0.4	
36	5.1±1.0	4.5±0.8	3.9±0.7	2.4±0.5		
37	6.2±1.1	6.2±1.1	5.1±0.9	2.8±0.6	1.9±0.4	

q	$\sigma^8_{q,q-2}$	$\sigma^9_{g,g-2}$	$\sigma^3_{q,q-3}$	$\sigma^4_{q,q-3}$	$\sigma^5_{q,q-3}$	$\sigma^6_{q,q-3}$
20			0.5±0.09	0.8±0.1	1.1±0.1	
28	0.5±0.06	0.5±0.05	0.1±0.03	0.2±0.03	0.3±0.04	0.5±0.05
30	0.7±0.08	0.4±0.06	0.3±0.06	0.4±0.07	0.5±0.07	1.0±0.1
31	0.6±0.02					
32	1.4±0.2	0.6±0.1	0.4±0.09	0.4±0.09	0.8±0.1	0.7±0.1