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ABSTRACT.

We present a new assessment of cross section data for excitation of He(l ^{1}S) by proton impact at energies larger than 10keV (in a few cases 6keV). Data for excitation to n^{1}L states of He (n ≤ 4, L = S, P and D) are given in tables. The data at high energy (–1000keV) are linked to the first Born approximation and at low energies in some cases to the close coupling AO results of Fritsch, who also made a critical evaluation of the cross sections for excitation of He by protons.

Introduction.

A new assessment of proton impact cross-section data for excitation of helium from its 1^1S ground state is presented. Similarly as our studies of excitation of helium by electron impact [1] and electron capture from helium by protons [2], this work was initiated in connection with the installation and recent use of ^3He and ^4He neutral heating beams on the JET tokamak [3]. The impact energy range covered extends up to higher impact energies than the ones of direct interest for the present beam based diagnostics at JET (energies smaller 200 keV) in order to be also of relevance to possible future He beam based diagnostics. At ITER neutral heating beams of a few hundreds of keV/amu are foreseen to closer match the velocity of the fusion-produced alpha particles [4].

Schematically the processes studied here are given by

$$H^+ + He(1^1S) \longrightarrow H^+ + He^*(n^1L) \qquad (1)$$

Except for the 2^1S state, the excited states decay under photon emission and so it is appropriate to study helium excitation by means of photon emission spectroscopy with absolute intensity measurement. Therefore this papers brings back into memory the often forgotten compilation by Thomas [5] about optical experiments in ion-atom collisions. Besides it includes more recent work of this kind of the group of Schartner, e.g. refs. [6,7]. As mentioned before the 2^1S state of He cannot be observed optically and for the excitation of that state we have considered the energy loss experiments of the group of Park [8,9], who also measured the 2^1P excitation, for which optical work has only been performed by Hippler and Schartner [7]. The most recent compilation of cross section data has been provided by Barnett and coworkers [10]. Our recommended cross sections sometimes deviate from those given in that work.

Simultaneously with our study Fritsch [11] has made a critical evaluation of existing data for helium excitation in heavy-particle collisions, including proton impact, along with new calculations within the close coupling framework with atomic basis sets applied to excitation of He 2^1L and $3\,^1L$ levels. Our analysis for proton impact has a lot of overlapping with the work of Fritsch and therefore we only give some complementary and relevant information, i.e. data tables of recommended excitation cross sections.

Results and discussion

Compared with the compilation of Thomas [5] the principal new contribution in this paper is the inclusion of more recent experimental [6,7,9] and theoretical [11,12] work. We shall generally confine ourselves to impact energies above 10 keV. In the article of Thomas we can see that the cross sections obtained by the various groups often show approximately the same energy dependence, but differ in absolute scale. Therefore Thomas often applied a normalization procedure at one impact energy and then plotted the data again in one graph.

In order to establish an absolute scale we give generally preference to the data of Schartner's group [6,7] (for 2^1P, 3^1P and 4^1L levels) between 150 and 1000 keV, because at high energies they merge very well into the Born approximation. The corresponding cross sections have been calculated by Bell et al [13]. At these relatively high energies we assume for the missing levels (2^1S, 3^1S, 3^1D and n^1L ($n \geq 4$)) that the cross section ratio's in a term series are independent of energy and have the same value as in the Born approximation. It appears experimentally that this ratio is even approximately constant down to about 40 keV. Deviations then are largest for the lower levels in a term series where the difference in excitation energy is relatively the largest. This can be seen in the low energy experimental data of van den Bos et al [14] and the calculations of Fritsch [11] and Slim et al [12].

As we have remarked before, data below 150 keV often differ on absolute scale and have to be normalized. In this work we have often given preference to the optical data of van den Bos et al [14] between 1 and 150 keV and fitted them to the high energy data of Hasselkamp et al [6] and Hippler and Schartner [7] for the following two reasons: The energy dependence of the cross sections of van den Bos et al [14] is close to the average of various data sets as shown by Thomas [5] and in several cases their absolute scale agrees within experimental errors with that of Schartner's group [6,7]. The scaling factors for van den Bos' data used in the fitting procedure are mostly close to those of Fritsch [11] but deviate in a few cases as indicated furtheron.

Experimental energy loss measurements of Kvale et al [9] giving cross sections for 2^1S and 2^1P at 25, 50, 75 and 100 keV generally confirm the consistency of our procedure.

Table 1 summarises the primary choices of experimental data and theoretical data together with the assessments of the accuracy of the cross sections over the various energy intervals. Table 2 summarizes the recommended cross sections for excitation to the different He(n^1L) levels, $n \leq 4$ and L = S, P and D from the He(1^1S) ground state. For $n > 4$ we recommend to extrapolate the cross sections with the same ratios as in the Born approximation at 100 keV (see ref. [13] where these cross sections are tabulated up to 7^1S, 6^1P and 6^1D). For higher n-values one may extrapolate according to the n^{*-3} proportionality where n^* is the effective principal quantum number. All these extrapolated cross sections have approximately similar errors as the corresponding $n = 4$ levels at comparable impact energies.

Excitation to the n^1F (G, H,...) levels is relatively small and negligible.

Conclusions

As also pointed ou by Fritsch [11] the excitation cross sections for H^+ - He(1^1S) collisions are generally well established particularly in the energy range relevant for nuclear fusion applications, i.e. larger than 10 keV impact energy. The higher the impact energy, the more accurate cross sections have been obtained experimentally and theoretically. Near one thousand keV generally the theoretical Born values are expected to be within 5%. At lower impact energies optical experiments give data accurate to 10% down to about 150 keV and at still lower energies scaled experimental data are expected to be better than 10-30% from 100 keV down to 10 keV. Close coupling extended atomic orbital calculations have been used to predict missing experimental data for 2^1S and 2^1P at low energies [11] and appear to be consistent with experiment for 3^1S and 3^1P and 3^1D below about 30 keV.

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Table 1. $\mathrm{H}^+ + \mathrm{He}(1^1\mathrm{S}) \rightarrow \mathrm{H}^+ + \mathrm{He}(n^1\mathrm{L})$

state	energy (keV)	method	reference	accuracy
$2^1\mathrm{S}$	6 - 28	AO	Fritsch [11]	~20%
	40 - 150	11.6 $\sigma(4^1\mathrm{S})$	van den Bos [14]	20 - 10%
	150 - 1000	11.6 $\sigma(4^1\mathrm{S})$	Hasselkamp et al [6]	< 10%
	> 1000	Born	Bell et al [13]	< 5%
$3^1\mathrm{S}$	10 - 150	opt.exp. ×0.784	van den Bos [14]	30 - 10%
	200 - 1000	2.61 $\sigma(4^1\mathrm{S})$	Hasselkamp et al [6]	< 10%
	> 1000	Born	Bell et al [13]	< 5%
$4^1\mathrm{S}$	10 - 150	opt.exp.	van den Bos [14]	30 - 10%
	200 - 1000	opt.exp.	Hasselkamp et al [6]	< 10%
	> 1000	Born	Bell et al [13]	< 5%
$2^1\mathrm{P}$	6 - 28	AO	Fritsch [11]	~20%
	30 - 150	4.09 $\sigma(3^1\mathrm{P})$	van den Bos [14]	20 - 10%
	150 - 1000	opt.exp.	Hippler and Schartner [7]	< 10%
	> 500	Born	Bell et al [13]	< 5%
$3^1\mathrm{P}$	10 - 150	opt.exp. ×0.82	van den Bos [14]	30 - 10%
	150 - 1000	opt.exp.	Hippler and Schartner[7]	< 10%
	> 500	Born	Bell et al [13]	< 5%
$4^1\mathrm{P}$	10 - 150	opt.exp. ×1.25	van den Bos [14]	30 - 10%
	200 - 1000	opt.exp.	Hippler and Schartner [7]	< 10%
	> 1000	Born	Bell et al [13]	< 5%
$3^1\mathrm{D}$	10 - 150	opt.exp. × 0.8	van den Bos [14]	30 - 10%
	200 - 1000	1.88 $\sigma(4^1\mathrm{D})$	Hasselkamp et al [6]	< 10%
	> 1000	Born	Bell et al [13]	< 5%
$4^1\mathrm{D}$	10 - 150	opt.exp. × 0.9	van den Bos [14]	30 - 10%
	200 - 1000	opt.exp.	Hasselkamp et al [6]	< 10%
	> 1000	Born	Bell et al [13]	< 5%

Note: Fritsch [11] used the following correction factors in the case of the data of van den Bos [14]: 0.74 for $3^1\mathrm{S}$, 0.75 for $3^1\mathrm{P}$, 1.14 for $4^1\mathrm{P}$, 1.47 for $5^1\mathrm{P}$, 0.82 for $3^1\mathrm{D}$, 0.9 for $4^1\mathrm{D}$ and 1.12 for $5^1\mathrm{D}$.

Table 2. Recommended excitation cross sections (in units of 10^{-20} cm^2) for $H^+ + He(1^1S) \longrightarrow H^+ + He(n^1L)$

E(keV)	2^1S	3^1S	4^1S	2^1P	3^1P	4^1P	3^1D	4^1D
6	71.1			194.5			19.5	
8							27.0	
10	241	27.4	8.82	331.3	45.5	14.8	29.9	12.6
12.5		36.1	10.4				37.1	16.7
14	460			311.4				
15		43.1	11.5		89.3	32.5	38.7	16.5
17.5								13.5
20	598	84.6	20.6	295.3	101	40.0	29.9	11.6
25		112	33.8		100	40.0	21.8	10.2
28	536			428				
30		116	40.8	425	104	45.6	23.4	10.4
35			44.8	512	125	52.5	26.7	11.9
40	567	128	48.9	556	136	56.3	32.0	13.1
50	547	131	47.1	793	194	75.0	29.3	13.7
60	520	112	44.8	954	234	87.5	29.1	14.2
70	523	94.7	45.1	958	234	98.7	27.9	13.6
80	483	102.6	41.7	1152	282	117	25.8	13.3
90	451	89.3	38.9	1183	289	114	23.3	12.8
100	407	90.8	35.1	1273	311	119	21.6	11.4
110	372	83.0	32.1	1340	328	144	20.0	11.2
120	343	77.8	29.6	1306	320	131	18.9	10.3
130	317	67.6	27.3	1333	326	135	18.1	9.81
140	287	69.8	24.7	1350	330	129	17.1	8.91
150	256	63.7	22.1	1287	323	130	16.1	8.19
200	219	49.3	18.9	1211	299	117	12.8	6.0
300	145	32.6	12.5	1006	256	101	7.1	3.8
400	110	24.8	9.5	864	220	93	6.0	3.2
500	87	19.6	7.5	787	197	77	4.5	2.4
600	69.6	15.7	6.0	682	178	72	3.9	2.1
700	59.2	13.3	5.1	647	165	63	3.2	1.7
800	53.4	12.0	4.6	568	150	58	2.8	1.5
1000	41.8	9.4	3.6	505	129	51	2.1	1.1
				Born cross section (Bell et al [13])				
1000	39.2	8.83	3.38	502.6	124.2	49.9	2.035	1.08
1500							1.374	0.732
2000	19.78	4.46	1.71	304.2	75.1	30.1	1.037	0.552
3000	13.23	2.98	1.14	223.6	55.1	22.1	0.696	
4000	9.94	2.24	0.857	178.8	44.1	17.7	0.524	
5000	7.96	1.79	0.686	150.0	37.0	14.8	0.420	

ANNEX

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