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Electron capture from atomic hydrogen by multiply charged ions in low energy collisions

M. Bendahman (*), S. Bliman (*), S. Dousson (*), D. Hitz (*), R. Gayet (+), J. Hanssen (+),
 C. Harel (+) and A. Salin (+)

Agrippa-CEA-CNRS, Centre d'Etudes Nucléaires de Grenoble, 38041 Grenoble, France

(*) Centre d'Etudes Nucléaires de Grenoble, 38041 Grenoble, France

(+) Laboratoire des Collisions Atomiques (Equipe de Recherche CNRS n° 260),
 Université de Bordeaux I, 33405 Talence, France

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Résumé. — On a mesuré et calculé les sections efficaces de capture dans l'hydrogène atomique par des ions multi-chargés. Les expériences ont été faites avec les ions N^{q+} , O^{q+} et Ne^{q+} comme projectiles dans la gamme d'énergie $2q$ à $10q$ keV. On obtient en général un bon accord avec les mesures antérieures quand celles-ci sont disponibles. Les calculs utilisent la méthode moléculaire, avec facteurs de translation. Ils concernent les projectiles complètement épluchés avec une charge comprise entre 5 et 10 ainsi que $O^{6+}(1s^2)$ et $N^{5+}(1s^2)$. Le rôle de l'interaction cœur-électron actif est discuté. On obtient un bon accord entre la théorie et l'expérience. Tant les résultats expérimentaux que les résultats théoriques sont exempts d'oscillations en fonction de la charge du projectile dans le domaine d'énergie couvert par les expériences.

Abstract. — Cross section measurements and calculations are presented for electron capture by multiply charged ions from atomic hydrogen. The measurements were made for N^{q+} , O^{q+} and Ne^{q+} projectiles in the energy range $2q$ to $10q$ keV. Fair agreement is obtained with most earlier measurements when available. Molecular calculations, including translation factors, have been carried out for the case of fully stripped projectiles with charges between 5 and 10 as well as for $O^{6+}(1s^2)$ and $N^{5+}(1s^2)$ impact. The role of the interaction between the core and active electron is discussed. Good agreement is obtained between theory and experiment. It is worth noting that both experimental and theoretical results do not show any oscillation as a function of the projectile charge in the energy range covered by the experiments.

1. Introduction.

The process whereby a multiply charged ion captures an electron from a hydrogen atom has received considerable attention — both theoretically and experimentally [1-9, 38]. In magnetically confined plasmas, these collisions not only strongly affect the ionization but also affect the penetration and energy deposition of injected H_0 neutral beams [10]. In astrophysics, charge transfer in slow collisions is important in reducing the degree of ionization of highly charged ions thus contributing to radiation [11-13].

Atomic hydrogen is an important target gas for the development and testing of theoretical models for electron capture processes. On the theoretical side, the situation is somewhat confusing. Whereas electron capture from atomic hydrogen has been the subject of most theoretical studies on multicharged ion atom

interaction, the results are still controversial. In particular, some authors [14, 15] have predicted oscillations as a function of the projectile charge, in contradiction with the results obtained by others [16, 17]. However the requirements for a meaningful determination of total capture cross sections within the molecular theory of atomic collisions have progressively been met, so that a quantitative evaluation seems possible without too much effort. In particular, Errea *et al.* [18] have discussed a choice of translation factor adapted to the present processes. Using this choice we now give an extensive discussion of the variation of the charge exchange cross section with projectile charge q for both stripped projectiles ($q = 5 - 10$) and projectiles carrying as $(1s)^2$ core ($q = 4 - 6$).

In the present work, we consider the collision of various ionic species where only one electron is

active, namely N, O, Ne in different charge states colliding with H(1s). The energy range of interest extends from 0.25 to 50.0 keV/amu for the theory and is restricted to approximately 1 to 5 keV/amu for the experiments. In section 2 the theoretical approaches for completely stripped ions and partially stripped ions colliding with H(1s) are described. In section 3, the experimental device is presented with the hydrogen dissociation oven and its calibration procedure; the results of measurements are given and compared with others when available. In section 4 results are discussed and compared with theory.

2. Theory.

2.1 FULLY STRIPPED PROJECTILES. — We are here interested in the determination of *total* charge exchange cross sections rather than the detailed distribution of final states produced in the process. We can, therefore, use the results of earlier studies of the problem [19-21] to set up the requirements for a determination of total charge exchange cross sections. The conclusions of these previous studies are :

(i) to determine the total population of final states with a given n , only one π and one σ state are important. Using the united-atom notation for the One Electron Diatomic Molecule (OEDM) these states are : $n, n-1, \sigma$ and $n, n-1, \pi$. For example, in the case of O^{8+} -H, only the $5g\sigma$ and $5g\pi$ states are required to determine the total population of the $n=5$ state of O^{7+} ;

(ii) there is, in general, one dominant value of n . However two (or sometimes three) adjacent values of n need be included in the calculations to obtain accurate results ;

(iii) crossings at large internuclear distances ($R > 15$ a.u. for $Z \sim 5-10$) do not contribute to the charge exchange process and may be « diabaticized » as explained in [19, 20]. Such diabatic states are labelled here with an index « d ».

In table I we give the states considered for each system. Most calculations have been carried out with five states : the entrance diabatic σ state, two σ states and two π states, as defined in (i), leading to charge exchange channels with adjacent values of n . For F^{9+} and Ne^{10+} projectiles, we have carried out a seven state calculation to evaluate the contribution of the $n=5, n=6$ and $n=7$ states.

An important requirement on the calculations is the proper treatment of the momentum transfer to the electron in the process of charge transfer [22]. For the present case where transitions occur at large distances, a common translation factor has been proposed by Errea *et al.* [18] :

$$U(\underline{r}, t) = f\underline{v} \cdot \underline{r} - \frac{1}{2} f^2 v^2 t; f(R) = \frac{R}{R^2 + \beta^2} Z \quad (1)$$

where \underline{v} is the velocity of the incident projectile with

Table I. — *States considered in the calculations for one-electron systems.*

	States	Asymptotic limit
B^{5+} -H	$5g\sigma$	$B^{5+} + H(1s)$
	$(4f\sigma) (4f\pi)$	$B^{4+}(n=4) + H^+$
	$(3d\sigma) (3d\pi)$	$B^{4+}(n=3) + H^+$
C^{6+} -H	$(5g\sigma)_d$	$C^{6+} + H(1s)$
	$(6h\sigma)_d (5g\pi)$	$C^{5+}(n=5) + H^+$
	$(4f\sigma) (4f\pi)$	$C^{5+}(n=4) + H^+$
N^{7+} -H	$(6h\sigma)_d$	$N^{7+} + H(1s)$
	$(5g\sigma)_d (5g\pi)$	$N^{6+}(n=5) + H^+$
	$(4f\sigma) (4f\pi)$	$N^{6+}(n=4) + H^+$
O^{8+} -H	$(7i\sigma)_d$	$O^{8+} + H(1s)$
	$(6h\sigma)_d (6h\pi)$	$O^{7+}(n=6) + H^+$
	$(5g\sigma) (5g\pi)$	$O^{7+}(n=5) + H^+$
F^{9+} -H	$(7i\sigma)_d$	$F^{9+}, Ne^{10+} + H(1s)$
	$(8j\sigma)_d (7i\pi)$	$F^{8+}, Ne^{9+}(n=7) + H^+$
	Ne^{10+} -H	$(6h\sigma) (6h\pi)$
$(5g\sigma) (5g\pi)$		$F^{8+}, Ne^{9+}(n=5) + H^+$

The index d designates a diabatic state (see text).

respect to the target, \underline{r} is the electron position vector and $Z = \underline{r} \cdot \underline{v}$. The parameter β has been set equal to 0.1 and we have checked the independence of the results on β ($\beta < 1.0$) and on the choice of « privileged » origin [18]. The impact parameter method can then be used for the calculation of cross sections after trivial modifications of the program PAMPA [23].

2.1.1 Comparison with the results of Green *et al.* [20]. — For C^{6+} -H and O^{8+} -H, we may compare our results with the 33-state calculation of Green *et al.* [20]. Besides the dimension of the basis set it should be noted that we have not used the same translation factors as them. Data are given in table II. Agreement is very good for carbon, particularly when one notes that more final values of n were included in their calculations. The maximum difference is about 10 %. In the case of oxygen projectiles the difference is larger, partly because we neglect the $n=3$ state. However, there is still a large discrepancy in the cross section for the formation of $O^{7+}(n=6)$. As already noted by Shipsey *et al.* [20], the cross sections for individual values of n are more sensitive to the basis than the total charge exchange cross-sections. In this respect two points are important :

1) Transitions between excited states formed by capture are non-negligible at large energies.

2) For O^{8+} -H such transitions occur for large internuclear distances ($R \sim 20$ a.u.). Since we integrate the coupled equations to a value of R much smaller than in [20], slight differences in cross sections for a given n could be expected. Still this does not explain the appreciable difference encountered here.

Table II. — Charge exchange cross section for the reaction $I^{q+} + H(1s) \rightarrow I^{(q-1)+}(n) + H^+$ in 10^{-16} cm^2 . Comparison with the results of Green et al. [20].

a) $C^{6+}-H$:			
Velocity (a.u.)	0.4569	0.6856	1.041
Energy (keV/amu)	5.22	11.75	27.0
This work	$n = 5$	6.41	10.3
	$n = 4$	36.4	30.8
	Total	42.8	41.1
Green et al.	$n = 5$	9.5	12.5
	$n = 4$	36.6	29.0
	Total	47.7	46.0
b) $O^{8+}-H$:			
Velocity (a.u.)	0.4569	0.6856	1.167
Energy (keV/amu)	5.22	11.75	34.0
This work	$n = 6$	12.6	14.9
	$n = 5$	43.8	38.8
	Total	56.4	53.7
Green et al.	$n = 6 \text{ or } 7$	17.4	21.0
	$n = 5$	45.0	36.1
	Total	66.5	62.1

In conclusion, we may estimate the error as smaller than the relative error in the experiment (see 4.2.1). The restriction of our basis to five states probably leads us to underestimate the true results by a few percent.

2.1.2 Results and discussion. — Our results are given in table III and figures 1-7 together with those of earlier theoretical work. It can be seen that the total capture cross sections do not vary much with energy for impact energies larger than 1 keV/amu. Below this limit, the increase of the cross section for decreasing energies should be noted in the case of $N^{7+}-H$ and $F^{9+}-H$. It can be explained by the characteristics of the crossing located between 12.5 and 13 a.u. : the cross section maximum due to this crossing occurs at lower velocities. Our results are close to those of Fritsch and Lin [17], Lüdde and Dreizler [16] and Bottcher [24]. The good agreement obtained with the latter authors gives us confidence in the accuracy of our results which have benefitted from the experience from earlier calculations with the MO expansion. The results of Grozdanov [33] for O^{8+} and Ne^{10+} impact underestimate ours by 10 to 20 %. An appreciable discrepancy can be observed with the multi-channel Landau-Zener approximation (MLZRC) of Janev et al. [15].

The MLZRC approximation can be considered as an approximation to a coupled molecular state calculation if the same states are used in both methods. In the (MLZRC) method of Janev et al. [15], more states are introduced than in our calculations :

— states correlated with n values not considered in our work. However, it can be seen from their results that these n values contribute negligibly to the total charge exchange cross section ;

— an approximate expression has been used in [15]

Table III. — Capture cross section for the reaction $I^{q+} + H(1s) \rightarrow I^{(q-1)+}(n) + H^+$ in 10^{-16} cm^2

v (a.u.)	0.1	0.2	0.4	0.6	0.8	1.0	1.414
E (keV/amu)	0.25	1.0	4.0	9.0	16.0	25.0	50.0
$B^{5+}-H$	$n = 4$	14.5	16.4	19.8	19.6	18.9	17.6
	$n = 3$	ϵ	1.1	8.5	11.3	11.0	10.8
	Total	14.5	17.5	28.3	30.8	30.0	28.3
$C^{6+}-H$	$n = 5$	1.5	1.8	5.2	9.1	10.6	11.3
	$n = 4$	19.2	36.3	37.3	31.6	29.3	25.7
	Total	20.8	38.1	42.5	40.6	39.9	36.8
$N^{7+}-H$	$n = 5$	62.1	45.9	33.2	27.2	24.1	20.2
	$n = 4$	0.1	3.6	16.3	19.2	17.9	17.6
	Total	62.2	49.5	49.5	46.4	42.0	37.8
$O^{8+}-H$	$n = 6$	4.25	5.45	12.0	14.7	14.8	15.6
	$n = 5$	23.2	48.2	45.4	40.1	36.5	30.8
	Total	27.5	53.7	57.4	54.8	51.3	46.4
$F^{9+}-H$	$n = 7$	1.4	1.33	3.61	4.43	8.14	12.3
	$n = 6$	74.1	60.8	40.2	34.7	29.6	27.5
	$n = 5$	0.82	9.3	25.3	25.5	22.9	18.6
	Total	76.4	71.4	69.1	64.6	60.7	58.3
$Ne^{10+}-H$	$n = 7$	3.4	3.9	7.9	8.8	9.5	10.7
	$n = 6$	40.8	62.1	50.3	39.2	37.1	33.0
	$n = 5$	ϵ	0.8	8.9	15.6	12.4	13.5
	Total	44.2	66.9	67.1	63.6	59.0	57.3

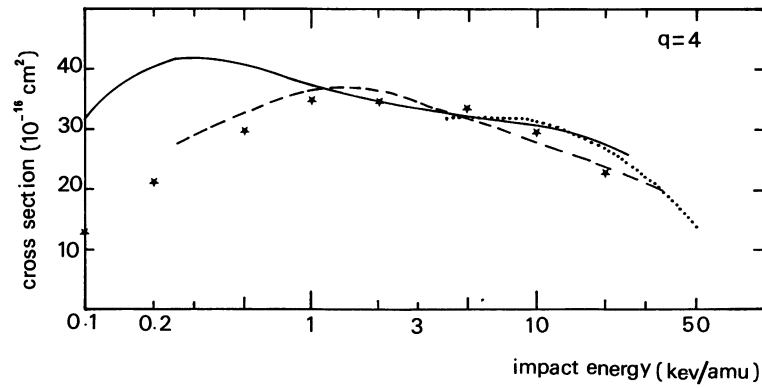


Fig. 1. — Total electron capture cross section from atomic hydrogen by Be^{4+} and $\text{C}^{4+}(1s^2)$ impact : Be^{4+} : --- [18], ★ [17], ●●● [16]; C^{4+} : — [31].

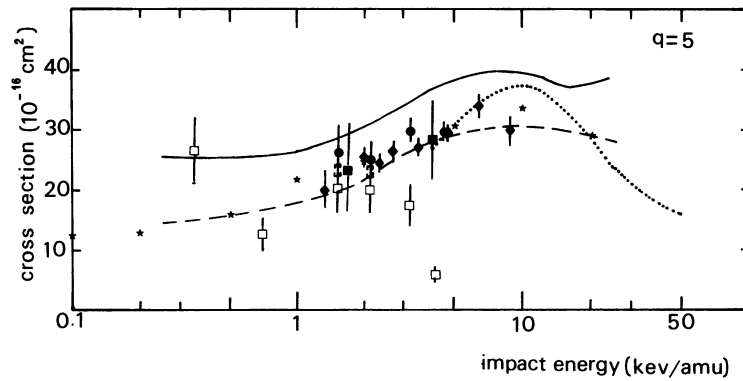


Fig. 2. — Total electron capture cross section from atomic hydrogen by B^{5+} and $\text{N}^{5+}(1s^2)$ impact : B^{5+} : --- present results, ★ [17], ●●● [16]; N^{5+} : Theory : — [31]; Experiment : ■ present results, □ [1], ◆ [8], ● [4].

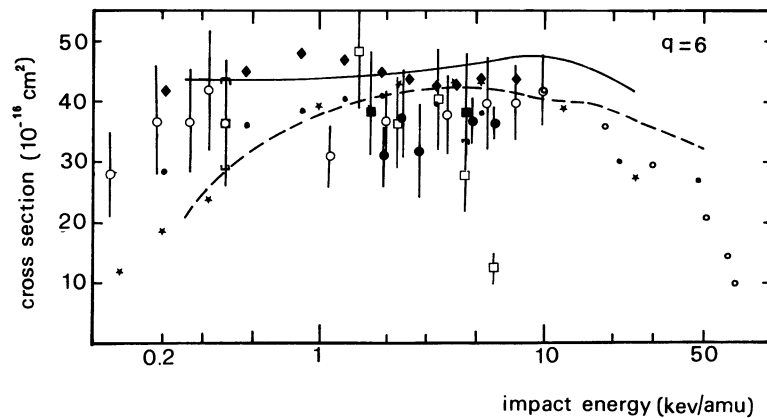


Fig. 3. — Total electron capture cross section from atomic hydrogen by C^{6+} and O^{6+} impact : C^{6+} : Theory : --- present results, ★ [17], ● [15], ○ [24]; Experiment : ■ present results, □ [1]; O^{6+} : Theory : — [31], ◆ [32]; Experiment : ○ [2], ♣ [8].

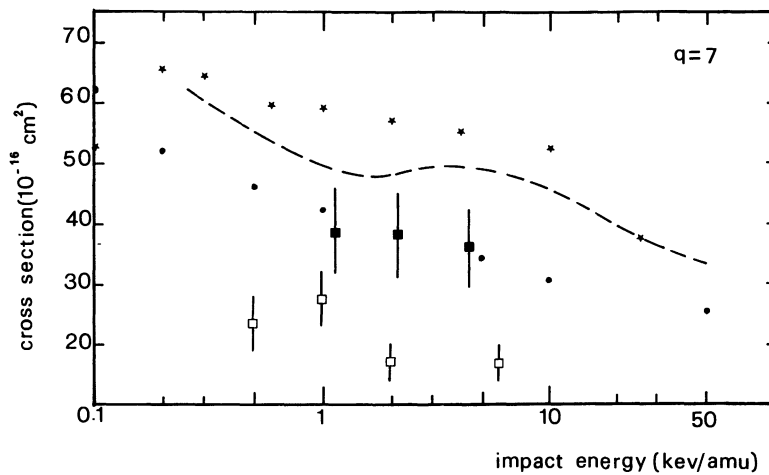


Fig. 4. — Total electron capture cross section from atomic hydrogen by N^{7+} impact : Theory : — — — present results, ★ [17], ● [15]; Experiment : ■ present results, □ [1].

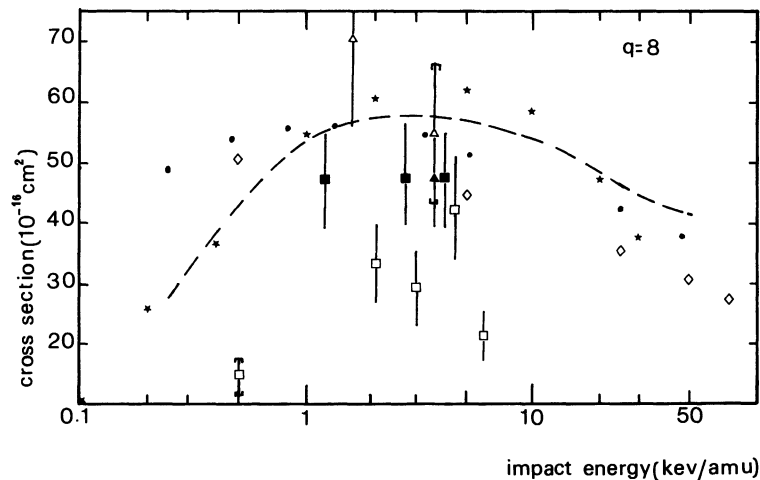


Fig. 5. — Total electron capture cross section from atomic hydrogen by O^{8+} and Ne^{8+} impact : O^{8+} : Theory : — — — present results, ★ [17], ● [15], ◇ [33]; Experiment : ■ present results, □ [1]; Ne^{8+} : Experiment : ▲ present results; △ [1] (most data points are too large to fit into the figure).

to account for the rotational coupling to all quasi degenerate Stark states inside the crossing distance. However, as we have recalled above (condition ii), it has been shown [20, 21] that only one π state (the one introduced in present calculations) plays a role for the global population of a given n state.

Hence, the difference between our results and the MLZRC measures the inaccuracy of the latter. It can be seen that this difference is non negligible in most cases, particularly for the larger values of Z . Furthermore the n distribution is quite different from ours (compare figures 8-12 of [15] with the results of table III). Part of the difference is due to the breakdown of the Landau-Zener approximation discussed below (particularly for $Z = 7$ and $Z = 9$). For

example, in the case of F^{9+} -H, Janev *et al.* find a cross section smaller than 10^{-18} cm^2 for $n = 7$ at 10 keV/amu whereas our result is $4.43 \times 10^{-16} \text{ cm}^2$.

In the special case of B^{5+} -H, our results are close to those of Fritsch and Lin and disagree with those of Kimura and Thorson [25] for energies smaller than 5 keV/amu. The calculations of Kimura and Thorson differ from ours by the addition of the $3 p\sigma$ state in the expansion and a different choice of translation factor.

It is interesting to study the charge exchange process as a function of the charge q of the projectile. In figure 8 we give the cross section as a function of q for three impact energies : 0.25, 1 and 9 keV/amu. It can be seen that no oscillation exists for energies larger than 1 keV/amu whereas large oscillations appear for

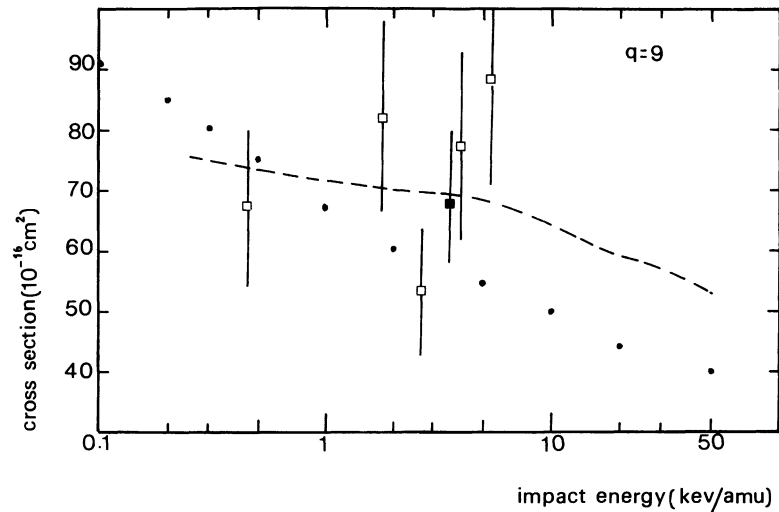


Fig. 6. — Total electron capture cross section from atomic hydrogen by F^{9+} and Ne^{9+} impact : F^{9+} : Theory : — — present results, ● [15]; Ne^{9+} : Experiment : ■ present results; □ [1] (a point at 0.9 keV/amu is too large to fit into the figure).

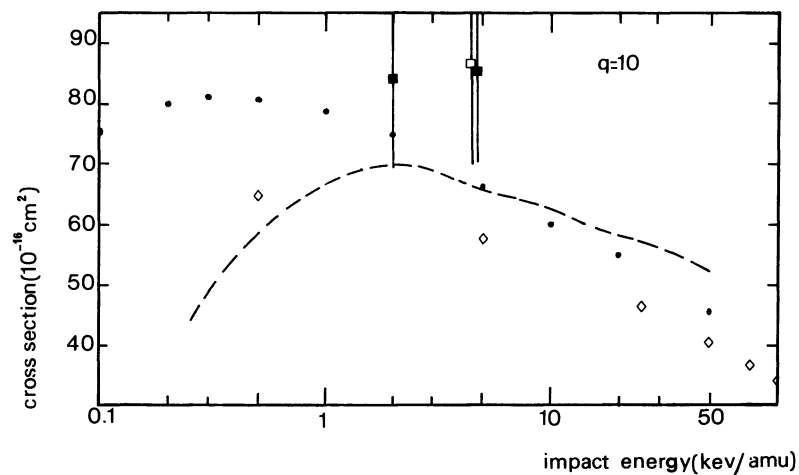


Fig. 7. — Total electron capture cross section from atomic hydrogen by Ne^{10+} impact : Theory : — — present results, ● [15], ◇ [33]; Experiment : ■ present results, □ [1] (most data points are too large to fit into the figure).

lower energies. A simple interpretation can be given. Consider transitions to a given final value of n . The distance R_c^n at which a pseudo-crossing with the entrance channel occurs decreases as q increases. The separation between the potential curves at the crossing also increases. Hence the system has a diabatic behaviour at this crossing for large R_c^n and an adiabatic behaviour for small R_c^n , which means that transitions to a given n have a maximum for some value $q = q_{max}^n$. The value of q_{max}^n increases with n . If this maximum in the cross section for q_{max}^n is sharp, when one sums over n values for a given q to determine the total capture cross section, the latter quantity oscillates with q . Such a sharp maximum is obtained, for example, with the two-state Landau-Zener model or

in the work of Duman *et al.* [26]. This explains the origin of the oscillations at low energies. However a different situation prevails for larger energies. For example, in the case of $O^{8+}-H$, transitions to $O^{7+}(n=6)$ are not due to the crossing at $R_c \sim 17.5$ a.u. which is completely diabatic in the energy range considered here. Calculations show that transitions to the $(6h\sigma)_d$ state are quite important for $10 < R_c < 18$ a.u. This break-down of the Landau-Zener approximation has a simple interpretation which was pointed out by Borondo *et al.* [27, 28] in the case of H^+-H^- : the appropriate model is Nikitin's exponential model. Borondo *et al.* have shown that for transitions taking place at large internuclear distance, the exponential model tends to a combination of

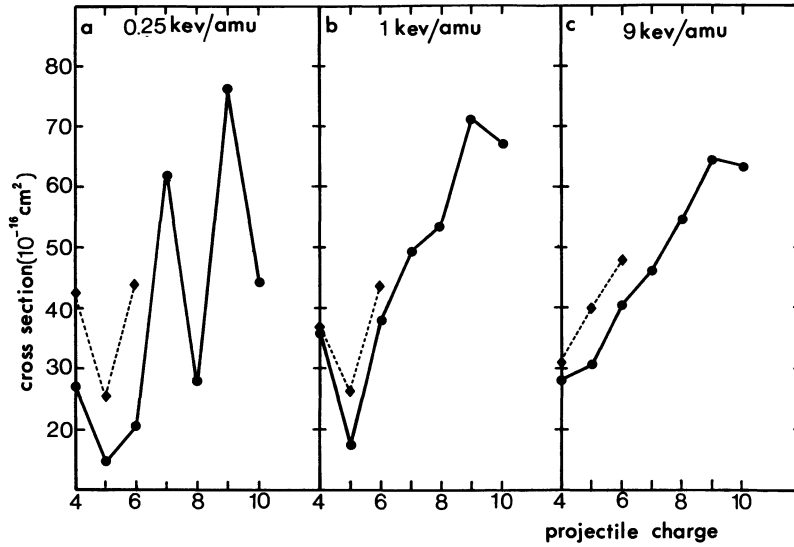


Fig. 8. — Total theoretical cross section for electron capture by multicharged ions from atomic hydrogen as a function of the projectile net charge : a) 0.25 keV/amu, b) 1 keV/amu, c) 9 keV/amu. ● present results for fully stripped projectiles ; ◆ results for projectiles with a (1s)² core [31].

the Landau-Zener model (at the crossing) and the Demkov [30] model (see appendix II of [28]). This is exactly what we observe in the case of O⁸⁺-H where the (6hσ)-(7iσ)_a process is dominated by transitions inside the crossing distance (i.e. they should be described by the Demkov model). The variation with both energy and projectile charge is then quite different from that of the Landau-Zener model which explains why the oscillations vanish at large energies. A detailed study of this problem will be published elsewhere.

2.2 PROJECTILES WITH A (1s)² CORE. — Calculations have been carried out for C⁴⁺(1s²), N⁵⁺(1s²) and O⁶⁺(1s²) projectiles. A summary of the methods and results has already been published [31]. The molecular properties are determined through a model-potential approach and the collision problem is solved with the same approximations as for fully stripped projectiles. However the model-potential assumption breaks down at small internuclear distances since the atomic cores overlap and we have accordingly not

made calculations for impact-parameters smaller than 2 a.u. This procedure can introduce at most an error of 3.5 × 10⁻¹⁶ cm² in the cross sections and allows us, on the other hand, to set β = 0 in the form of the common translation factor (1). Results are given in table IV.

It is of interest to compare the results for systems carrying the same charge q with and without a core. This is done in figures 1 to 3. For q = 4 and 6, both sets of results are very close at energies larger than 1 keV/amu. However large differences are observed for lower energies. This difference can be attributed to the crossing with the σ 4p state (resp. σ 3p) for O⁶⁺ (resp. C⁴⁺) which is not diabatic for velocities smaller than 1 keV/amu whereas the crossing with the 4dσ (resp. 3pσ) is negligible in the case of C⁶⁺ (resp. Be⁴⁺). We can thus interpret the difference at low energies observed between the experiments (the bulk of them did not use fully stripped ions) and theory (generally done with fully stripped projectiles). This is also corroborated by experimental evidence [3].

Table IV. — Capture cross section (in 10⁻¹⁶ cm²) for the reaction I^{q+}(1s²) + H(1s) → I^{(q-1)+}(1s², n) + H⁺

v (a.u.)	0.063	0.1	0.2	0.4	0.6	0.8	1.0
E (keV/amu)	0.1	0.25	1.0	4.0	9.0	16.0	25.0
C ⁴⁺ -H n = 3	31.6	42.0	37.0	32.5	30.7	29.2	25.9
N ⁵⁺ -H	n = 3	0.2	2.7	9.9	9.3	7.9	8.2
	n = 4	25.2	23.6	27.1	30.5	29.7	31.0
	Total	25.4	26.4	37.0	40.0	37.6	39.2
O ⁶⁺ -H	n = 4	40.8	42.6	42.3	41.0	34.2	29.5
	n = 5	2.8	1.0	3.6	6.9	11.3	12.7
	Total	43.6	43.6	45.9	47.9	45.5	42.2

The case $q = 5$ is more specific. The most important pseudo-crossing occurs at $R_c = 11.7$ a.u. for N^{5+} whereas it occurs at $R_c = 13.0$ a.u. for B^{5+} . In other terms, the relative influence of the core-active electron interaction is much larger for these distances. Besides the change of position of the crossing, there is also a modification of character of the $\sigma 4s$ state : instead of being a pure « Stark » state in the vicinity of R_c (as in the case of O^{6+}), it has a larger $4s$ component, which influences the strength of the $\sigma 1s(H)$ - $\sigma 4s(N)$ and $\sigma 1s(H)$ - $\sigma 4p(N)$ couplings. As the rule (i) given in section 2.1 is closely related to the Stark character of OEDM states, it is not surprising that we observe a larger effect of the core electrons in the case of N^{5+} .

Our results can be compared with those of Olson *et al.* [32]. Agreement is obtained within 10 % in the energy range considered here.

3. Experimental device and dissociator's calibration procedure.

The experimental arrangement is basically the same as previously described [34] except for the atomic hydrogen target.

Multiply charged ions are extracted from an E.C.R. ion source : they are charge and mass analysed by a first 168° double focusing magnet. The ions of a chosen charge to mass ratio pass along the axis of a cylindrical hydrogen dissociation oven. The product ions are analysed by a second magnet (identical to the first one) at the exit of which they are collected in a Faraday cup.

3.1 THE HYDROGEN DISSOCIATION OVEN. — The dissociation oven designed for the present measurements is basically made of a thin walled (25 μm) 12 cm long and 1.4 cm inner diameter tungsten cylinder, mounted

on two molybdenum end pieces. The hydrogen gas is flown into the centre of the tungsten tube through a small hole; the actual target region (10 cm long) is limited by entrance and exit apertures in the end pieces with hole diameters of 4 and 8 mm. Heating is accomplished by passing a DC current through the tungsten tube; typical heating conditions are 170 A at 12 V corresponding to a furnace temperature not exceeding 2400K. The furnace is shielded from radiation by a thick molybdenum wall. The entire assembly is located in a double walled water cooled copper housing. Provision is made for allowing optical observation of the collision process : a small (1 \times 8 mm) slit parallel to the ion beam axis has been cut in the oven wall, heat shielding and surrounding housing (Fig. 9). A detailed description of the oven design and characteristics can be found in [39].

3.2 CALIBRATION PROCEDURE. — Since the cross sections for electron capture are deduced from the growth rate method, the target thickness need be determined. In the case of hydrogen, the supply to the dissociator is molecular hydrogen; thus two interrelated quantities relevant to the H target thickness determination are the dissociated fraction f and the degree of dissociation D .

$$f = p(H)/[p(H) + 2p(H_2)] = \pi(H)/[\pi(H) + 2\pi(H_2)] \quad (2)$$

where $\pi(H)$ and $\pi(H_2)$ are the target thickness of H and H_2 , $p(H)$ and $p(H_2)$ being the respective partial pressures [4]

$$D = p(H)/[p(H) + p(H_2)] = \pi(H)/[\pi(H) + \pi(H_2)]. \quad (3)$$

Thus $f = D/(2 - D)$.

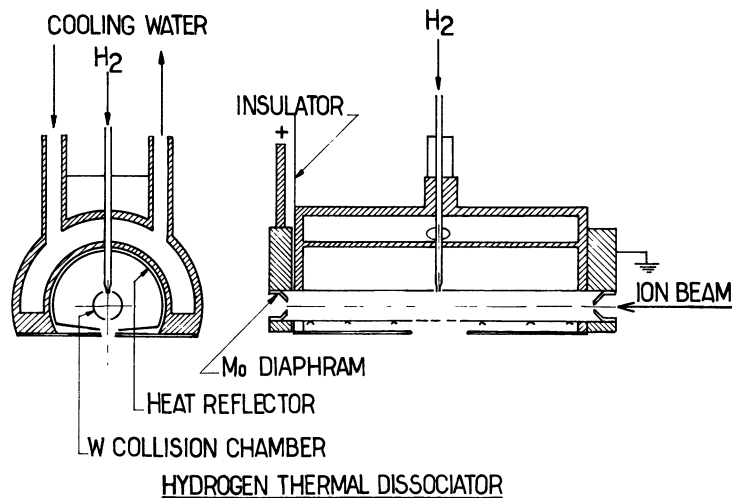


Fig. 9. — Schematic diagram of the hydrogen dissociation oven.

Denoting by p_0 the total hydrogen pressure in the target (viz $p_0 = p(\text{H}) + p(\text{H}_2)$) and by π_0 the total target thickness, we may write :

$$\pi_0 = \pi(\text{H}) + \pi(\text{H}_2)$$

or

$$p_0 = p(\text{H}) + p(\text{H}_2) = \beta P.$$

In this last expression, P is the pressure in the volume surrounding the oven; it expresses the proportionality of the target pressure to that of the volume around it (at oven constant temperature and constant gas flow into the oven).

With these quantities, the cross sections are expressed through the knowledge of reduced cross sections $\Sigma_{q,q-1}$ which are the measured quantities

$$\begin{aligned} \Sigma_{q,q-1} &= D\sigma_{q,q-1}(\text{H}) + (1 - D)\sigma_{q,q-1}(\text{H}_2) \\ &= (I_{q-1}/I_q)/\beta P \end{aligned} \quad (4)$$

I_{q-1} is the current associated with the particles resulting from capture.

I_q is the current associated with the primary ions of charge q .

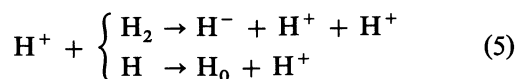
Calibration of the H_0 target is needed : two procedures may be used.

The first one uses the collision processes $\text{H}^+ \rightarrow \text{H}^-$ (double capture on H_2 which gives D , degree of dissociation) and $\text{H}^+ \rightarrow \text{H}_0$ (single capture which gives the target thickness). The lack of a method to detect H_0 prevented us from doing a direct measurement of the target thickness. The second procedure consists in determining β and D (see the above-mentioned relations for $\Sigma_{q,q-1}$) by remeasuring $\sigma_{q,q-1}$ for different ions at fixed energies [4, 6, 9]. Since for certain ions, both $\sigma_{q,q-1}(\text{H})$ and $\sigma_{q,q-1}(\text{H}_2)$ are known, measuring the reduced cross section $\Sigma_{q,q-1}$ gives a set of linear equations with two unknown quantities to be determined : D and β .

A detailed discussion of the calibration procedures and experimental conditions has been given in [40].

3.3 CALIBRATION RESULTS.

3.3.1 *First procedure.* — For determining D , one uses the collision processes :



under constant gas flow into the oven. When the temperature of the oven varies, the fraction of double capture varies. This is seen through the quantity :

$$F_{-1}(\text{H}, \text{H}_2) = I_{\text{H}^-}^*(\text{H}, \text{H}_2)/I_{\text{H}^-}(\text{H}_2) \quad (6)$$

where $I_{\text{H}^-}(\text{H}_2)$ is the current of H^- measured at zero heating power W to the oven and $I_{\text{H}^-}^*(\text{H}, \text{H}_2)$ is the H^- current when W is increased. A measure of the double capture cross section $\text{H}^+ + \text{Ar} \rightarrow \text{H}^- + \text{Ar}^{2+}$ as a

function of the heating power yields the ratio :

$$F_{-1}(\text{Ar}) = I_{\text{H}^-}^*(\text{Ar})/I_{\text{H}^-}(\text{Ar}) \quad (7)$$

where $I_{\text{H}^-}^*(\text{Ar})$ designates the H^- current when heating the oven. In the latter case, when the heating power is increased, it is observed that, after a slight decrease, the ratio $F_{-1}(\text{Ar})$ levels at a constant value (≈ 0.54) whereas $F_{-1}(\text{H}, \text{H}_2)$ still decreases and only levels at larger heating power at a constant value close to 0.08 for $T = 2\,400$ K. Combining these quantities [9], an expression for D is obtained :

$$D = \sqrt{2} [1 - F_{-1}(\text{H}, \text{H}_2)/F_{-1}(\text{Ar})] / [(1 - \sqrt{2}) F_{-1}(\text{H}, \text{H}_2)/F_{-1}(\text{Ar}) + \sqrt{2}]. \quad (8)$$

Considering the F_{-1} values shown in figure 10, the actual value of D is set to 0.88. This value is consistent with the values obtained in earlier studies using this technique [1, 4, 8, 9].

3.3.2 *Second procedure.* — This procedure gives both D and β . At a fixed temperature, D is constant. If then the gas supply is varied in a limited range, so that the single collision condition is fulfilled, $\Sigma_{q,q-1}$ can be deduced (growth rate method); utilizing ions for which both $\sigma_{q,q-1}(\text{H})$ and $\sigma_{q,q-1}(\text{H}_2)$ are known, we are left with a linear equation with two unknowns : D and β . In principle it suffices to solve two equations for these two unknowns. In our case, we have performed the calibration with four different ions O^{4+} , O^{5+} , O^{6+} [2, 8] and N^{4+} [4, 8, 35] for which capture cross sections from H and H_2 are known. Solving graphi-

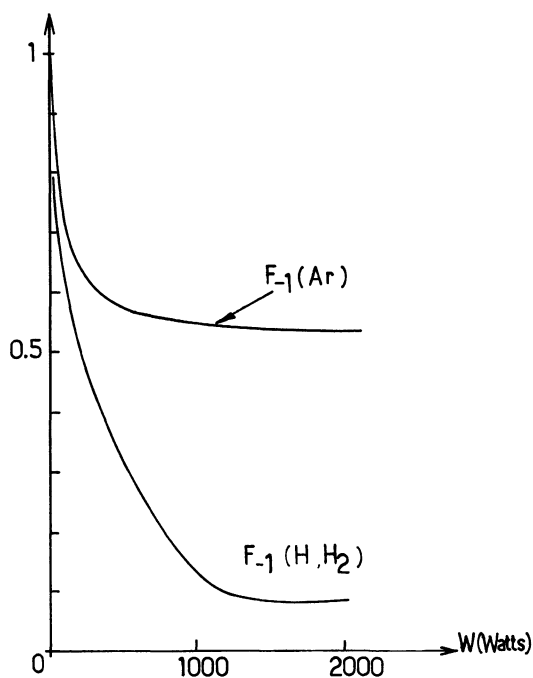


Fig. 10. — Evolution of double capture fraction with heating power W fed into the dissociator.

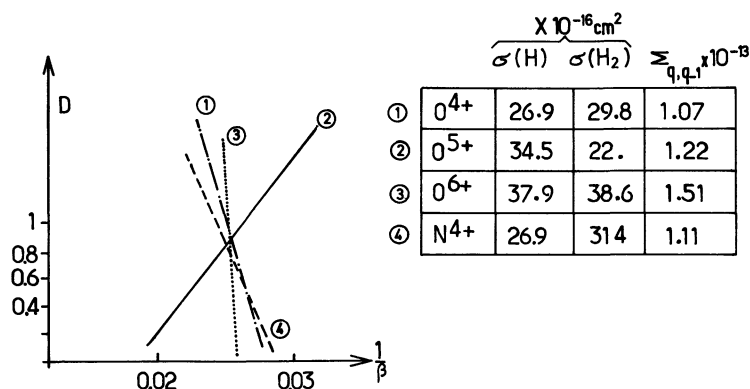


Fig. 11. — Calibration of the dissociator for D and β (see text).

cally gives $D = 0.88$ and $\beta \approx 39.2$. This is shown in figure 11. The calibration procedure, which uses previously measured cross sections, might be sensitive to errors on these cross sections: the relative error between $\sigma(\text{H})$ and $\sigma(\text{H}_2)$ or the errors on their absolute values. The relative error between $\sigma(\text{H})$ and $\sigma(\text{H}_2)$ causes a relative error between D and β . The error on the absolute values of $\sigma(\text{H})$ and $\sigma(\text{H}_2)$ affects β but has no influence on D . Therefore it is significant to note that the two independent calibration procedures gave values for D in excellent agreement.

4. Experimental results and discussion.

The cross sections for electron capture from atomic hydrogen have been measured in the energy range $2q$ to $10q$ keV where q is the incident ion charge. The ions are either completely stripped (N^{7+} , O^{8+} , Ne^{10+}) or not (N^{q+} for $q > 4$; O^{q+} for $q > 4$ and Ne^{q+} for $q > 5$). We consider separately the ions with a closed $1s^2$ shell.

4.1 CROSS SECTION MEASUREMENTS.

4.1.1 Fully stripped ions. — The specific ions are here: $^{15}\text{N}^{7+}$, $^{18}\text{O}^{8+}$, $^{22}\text{Ne}^{10+}$. In the covered energy range (1 to 4.5 keV/amu) no significant variation is seen in the capture cross section for a given ion within the experimental accuracy.

The salient feature is a regular increase in total capture cross sections when the charge increases; typical mean values are given in table V.

The cross section for N^{7+} decreases slightly with increasing energies whereas it is constant for O^{8+} and Ne^{10+} as shown in figures 4, 5 and 7. Good agreement is obtained with theory for N^{7+} and O^{8+} ; however for Ne^{10+} the two results differ by more than 20%. A large discrepancy should be noted with the previous experimental results of Panov *et al.* [2] particularly as regards the energy dependence.

4.1.2 Incident ions with a $1s^2$ shell. — For these ions, as for those considered later, specific isotopes are used when contamination is possible from impurities with the same charge to mass ratio produced by the

Table V. — Experimental electron capture cross section by I^{q+} from atomic hydrogen (in 10^{-16} cm^2).

	Projectile	Cross section
$q = 4$	N^{4+}	27
	O^{4+}	27
$q = 5$	N^{5+}	28
	O^{5+}	35
	Ne^{5+}	28
$q = 6$	N^{6+}	38
	O^{6+}	38
	Ne^{6+}	34
$q = 7$	N^{7+}	35
	O^{7+}	35
	Ne^{7+}	28
$q = 8$	O^{8+}	46
	Ne^{8+}	47
$q = 9$	Ne^{9+}	68
$q = 10$	Ne^{10+}	88

The cross sections hardly change with energy in the energy range 10 to 4.5 keV/amu.

The estimated error in the data is $\pm 18\%$.

ion source wall degasing. Again the observed trend is a regular increase of the cross section from N^{5+} to O^{6+} and Ne^{8+} as well as a quasi independence on energy for a given projectile. Typical values are given in table V. As can be seen from figures 2, 3 and 5, good agreement is obtained with most earlier measurements when available and with theory. Again the most noticeable discrepancy is with the experimental results of Panov *et al.* [2] as for the fully stripped ions. It should be also noted that the results for Ne^{8+} and O^{8+} are nearly equal.

4.1.3 Other partially ionized atoms. — The projectiles considered are N^{q+} ($q = 4, 6$), O^{q+} ($q = 4, 5, 7$), Ne^{q+} ($q = 5, 6, 7, 9$). The results, given in table V for an impact energy of $10q$ keV, do not change with energy in the explored energy range.

4.2 DISCUSSION.

4.2.1 Estimation of errors in the measurements. — The uncertainties have various sources associated with both the target thickness calibration and the individual cross section measurements.

The accuracy of the data is limited by the accuracy of the cross sections used for the calibration of the dissociator. As is seen in results published previously [2, 4] the uncertainties in these cross sections are $\pm 14\%$. Relative errors in D and/or β are estimated to be $\pm 3\%$. Since they depend on each other, they have to be added to give the combined error of $\pm 6\%$. The uncertainties in the reference cross sections and the cumulated errors in D and β are to be added in quadrature : this gives an overall calibration uncertainty of the order of $\pm 16\%$.

The uncertainty in each individual cross section arises from the determination of the slope of $\Sigma_{q,q-1}$ (standard beam target method) which depends on the uncertainty in D and in $\sigma_{q,q-1}(\text{H}_2)$. For D it has been estimated to be $\pm 3\%$; since hydrogen is incompletely dissociated an error appears due to $\sigma_{q,q-1}(\text{H}_2)$. The slope for $\Sigma_{q,q-1}$ depends on I_{q-1}/I_q and the uncertainty on currents seldom exceeds 5% .

To sum up, adding the different errors in quadrature gives an overall uncertainty in an individual cross section at the level of $\pm 18\%$ which is consistent with the uncertainties of previously published results [1, 9].

4.2.2 Variation with projectile charge. — It is of interest to compare the capture cross sections measured with different projectiles carrying the same charge. In general the results appear as depending only on the net charge of the projectile. There are still some noticeable discrepancies : $\text{Ne}^{7+}(1s^22s)$ and $\text{O}^{5+}(1s^22s)$.

The variation of the capture cross section with projectile charge for an energy of 4.5 keV/amu is given in figure 12 together with the theoretical findings. Within the limit of experimental errors (which is much smaller for relative values than for absolute values due to calibration) no oscillation with projectile charge can be observed both in the theory and the experiment except for a slight undulation around $Z = 7$. The oscillations predicted by [14] give, in this energy range, a ratio between maxima and minima of the order of 2-4, which is excluded by our experimental data. It is interesting to note that such oscillations have been observed, in the same energy range, in previous experiments on multi electron targets [36, 37]. We are thus lead to conclude that the latter observations should not be sought for in theoretical studies on one-electron systems since they seem to be specific of multi electron targets.

5. Conclusion.

For the first time we have carried out a systematic experimental and theoretical study of electron capture

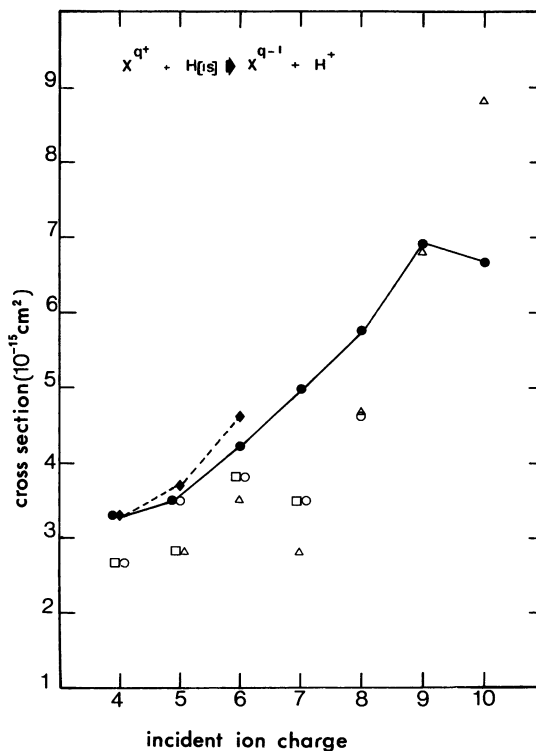


Fig. 12. — Total electron capture cross section by multiply charged ions from atomic hydrogen as a function of the projectile charge at 3.5 keV/amu. Experiment : Ne ions : Δ , O ions : \circ , N ions : \square ; Theory : ——— fully stripped projectiles ; - - - - - projectiles with a $1s^2$ core [31].

processes from atomic hydrogen by ions with charge q between 4 and 10, at collision energies of a few keV/amu. The most striking result seems to be the nearly monotonic increase of the cross section as a function of projectile charge. Oscillations predicted in this energy range were a direct consequence of the assumption that transitions occur only at the pseudo crossing between molecular curves connected with the entrance and charge exchange channels. However we have shown that transitions also occur by so-called « Demkov transitions » outside the crossings. For example, in the case of $\text{O}^{8+}-\text{H}(1s)$ collisions, transitions occur to $\text{O}^{7+}(n = 6)$ (from the entrance channel to the $6h\sigma$ state) between 10 and 17 a.u. Since such transitions become rapidly less important as the energy decreases, we still predict oscillations in the capture cross section as a function of projectile charge for impact energies smaller than 1 keV/amu. We therefore confirm that most charge exchange reactions should be treated by the Nikitin-Demkov model rather than the Landau-Zener model as first proved by Borondo *et al.* [27, 28].

Our work also confirms that there is no dramatic influence of the projectile electronic structure, except in a few cases. However further studies of this problem are required, particularly for heavier projectiles.

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