

Ionization of molecules by multicharged bared ions by using the stoichiometric model

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Abstract

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I. INTRODUCTION

The damage caused by the impact of multi-charged heavy projectile has become a field of interest because of the use in ion-beam cancer therapy. The effectiveness of the radiation depends on the choice of the ions. In particular, theoretical and experimental studies with different projectiles concluded that charged carbon ions could be the most suitable ion to use. This result opens a new challenge for the theoretical point of view since multi-charged atoms at not-so-high-velocities depart from the first Born approximation, which is the most popular theory used in this field. The first Born approximation, as any perturbative direct calculation, warrants the Z^2 laws, where Z is the projectile charge. However the damage concentrated in the vicinities of the Bragg peak correspond to energies of hundreds of KeV/amu, that is in the intermediate energy region. Precisely in this region, the Born approximation starts to fail. Another problem arises from the theoretical point of view; we are dealing with complex molecules. This article deals precisely with these two items. First, we perform more appropriate calculations on the primary damage mechanism, i.e., atomic ionization by multi-charged ions, which can replace the Born results. Second, we use and inspect the stoichiometric model, which reduces a molecule to a sum of atomic processes quantities weighted by the numbers of such atom in the molecule.

Since we have to deal with multi-charged ions, we resort to the Continuum Distorted Wave-Eikonal Initial State (CDW for short) which includes higher perturbative corrections. We start from the premise that the ionization process is the mechanism that deposits the most significant primary energy. This process produces an electron-energy spectrum that needs to be integrated. Also, these ejected electrons become a new source of local damage, which requires to be investigated because these quantities are used in Monte Carlo simulations. With this end in mind, we calculate not only the ionization cross-sections but also energy and mean angular values of the emitted electrons.

To deal with the molecules, we resort to the simplest stoichiometric model (SSM): we assume that the molecule is composed of isolated independent atoms. In all cases, the total cross-section is simply the sum of the cross-section of each atom.

With these two tools in mind, i.e., CDW instead of Born approximation and the SSM, we calculate ionization cross-section of different molecules (see Table I) by the impact of antiprotons, H^+ , He^{2+} , Be^{4+} , C^{6+} , and O^{8+} . In particular, in Section 3, we are interested in

DNA molecules such as Adenine, Timine, Cytosine, Guanine, Uracil, and DNA backbone.

The results are processed to test the Toburen scaling rule, which states that the ratio of the ionization cross-section divided by the number valence electrons (outer electrons) plotted in terms of the projectile velocity can be arranged in a narrow universal band. We have also applied this rule to several hydrocarbons and piramide molecules. We will prove that the width of the resulting universal band can be significantly reduced if we redefine the effective valence electrons as in Section 3.2.

It is well known that the residual electrons from the ionization process cause biological damage. To inspect this mechanism, in Section 3.3 and 3.4, we have calculated the mean electron energy an angular values. To our surprise, we found a substantial dependence of the charged projectile, which is unexpected in the first Born approximation.

To deal with projectiles of hefty charges, we resort to the CDW. However, the stoichiometric model used seems to be very simplistic since it considers each atom as neutral, which is not correct. In Section 3.5, we used the molecular electronic structure code GAMESS [1] to calculate the excess or defect of electron density one each atom. With this knowledge, we modify the simple stoichiometric model to account for the departure from neutrality. We find that, for the DNA molecules, this modification does not introduce a substantial change.

II. THEORY: IONIZATION OF ATOMS

In our study, we will consider six atoms $\alpha = \text{H, C, N, O, P, and S}$. Most of the organic molecules are composed of these atoms. Some particular molecules also include halogen atoms such as fluor and bromine; ionization cross-sections of these elements have been previously published [2, 3].

Total ionization cross-sections of these atoms were calculated using the CDW. The initial bound and final continuum radial wave functions were obtained by using the RADIALF code developed by Salvat and co-workers, using a Hartree-Fock potential obtained from the Depurated Inversion Model [4, 5]. We used a few thousand pivot points to solve the Schrödinger equation, depending on the number of oscillations of the continuum state. The radial integration was performed using the cubic spline technique. The number of angular momenta considered varied from 8, at very low ejected-electron energies, up to 30, for the highest energies considered. The same number of azimuth angles were required to obtain

the four-fold differential cross-section. The calculation performed does not display prior-post discrepancies at all. Each atomic total cross-section in Eq (1) was calculated using 35 to 100 momentum transfer values, 28 fixed electron angles, and around 45 electron energies depending on the projectile impact energy. See further details of the calculation in Ref. [6]. Simultaneously, we will be reporting state to state ionization cross sections for these cases in Ref. [7], which will be very useful to estimate molecule fragmentation.

In Figure 1, we report our results of total ionization of the six essential elements by the impact of six different projectiles, i.e., antiprotons, H^+ , He^{2+} , Be^{4+} , C^{6+} , and O^{8+} . To reduce the resulting 36 magnitudes into a single consistent figure, we use the fact that in the first Born approximation, the ionization cross-section scales with the square of the projectile charge, i.e., Z^2 . The values of the impact energies considered range between 0.1 to 10 MeV/amu, i.e., where the CDW is supposed to hold. In fact, for the highest projectile charges the minimum impact energy where the CDW is expected to be valid could be higher than 100 KeV. From some MeV/amu on, the first the Born approximation provides quite reliable results and using a much simpler formalism; we check it. We use the same color to indicate the projectile charge in all figures of this work: dashed-red, solid-red, blue, magenta, olive and orange for antiprotons, H^+ , He^{2+} , Be^{4+} , C^{6+} , and O^{8+} , respectively. Notably, there is no complete tabulation of ionization of atoms by the impact of multiple-charged ions. We hope that the ones presented in this article will be helpful.

III. IONIZATION OF MOLECULES

A. The stoichiometric model

Lets us consider a molecule M composed by n_α atoms of the element α , the SSM describes the total ionization cross section of the molecule σ_M as a simple sum of ionization cross sections of the isolated atoms σ_α , i.e.,

$$\sigma_M = \sum_{\alpha} n_{\alpha} \sigma_{\alpha} . \quad (1)$$

We divided sixteen molecular targets of our interest in 3 families. The classification we defined is given in Table I.

In Figure 2, we report the total ionization cross sections by the impact of multicharged ions for the four fundamental DNA components: adenine, timine, cytosine, and guanine.

CH	CH ₄ , C ₂ H ₂ , C ₂ H ₄ , C ₂ H ₆ , and C ₆ H ₆
CHN	C ₅ H ₅ N, C ₄ H ₄ N ₂ , C ₂ H ₇ N, and CH ₅ N
DNA	adenine (C ₅ H ₅ N ₅), timine (C ₅ H ₆ N ₂ O ₂), cytosine (C ₄ H ₅ N ₂ O), guanine (C ₅ H ₅ N ₅ O), uracil (C ₄ H ₄ N ₂ O ₂), DNA backbone (C ₅ H ₁₀ O ₅ P), dry DNA (C ₂₀ H ₂₇ N ₇ O ₁₃ P ₂)

TABLE I. Sixteen molecular targets of our interest classified in 3 families.

Our reports for uracil and DNA backbone containing P are given in Figure 3. For adenine, the agreement with the three experiments available in our range of validity is quite good. For uracil, we have a puzzling situation: our results show good agreement with the experiments by proton impact of Itoh *et al.* [8], but for the same target our theory fails by a factor of two for the impact of C⁴⁺ and O⁶⁺ ions. Nonetheless, it should be stated that our theoretical results coincide with the ones by Champion, Rivarola and collaborators [10, 11], which may indicate a possible misstep of the experiments.

B. Scaling rule

The first attempt to develop a comprehensive but straightforward phenomenological model for electron ejection from large molecules was posed by Toburen and collaborators [12, 13]. The authors found it convenient to scale the experimental ionization cross section in terms of the number of outer or weakly bound valence electrons (total number of electrons minus the inner-shell ones). We introduce the cross section per weakly bound electron or ionization cross section per valence electron, σ_e , as

$$\sigma_e = \frac{\sigma_M}{N_M} = \frac{\sum_{\alpha} n_{\alpha} \sigma_{\alpha}}{\sum_{\alpha} n_{\alpha} v_{\alpha}} = \sigma_e(v), \quad (2)$$

where

$$v_{\alpha} = \begin{cases} 4, & \text{for C,} \\ 5, & \text{for N and P,} \\ 6, & \text{for O and S,} \end{cases} \quad (3)$$

and $v_H = 1$. The Toburen rule can be stated by saying that σ_e is a *universal* parameter independent on the molecule, which depends solely on the impact velocity. In Ref. [13], it

was found experimentally that for proton impact on some simple molecules, σ_e results

$$\begin{array}{ccccc} E(\text{MeV}) & 0.25 & 1.00 & 2.00 & \\ \sigma_e(10^{-16}\text{cm}^2) & 0.39 & 0.17 & 0.11 & \end{array} \quad (4)$$

with an estimated error of about 20%. A similar ratio was found in Ref. [8] for proton impact on uracil and adenine. Figure 5a shows σ_e calculated with the CDW as a function of the impact velocity for different projectile charges computed with the SSM for the sixteen molecular targets displayed in Table I. The universality with Z is the one provided by Born approximation, i.e., $\sigma_e(Z) = Z^2\sigma_e(Z = 1)$, and it holds for large impact velocities, as shown Figure 5a. Obviously, for lower impact velocities the distorted wave CDW breaks this behavior discarding the rule Z^2 . Although the Toburen rule holds for high energies, its performance is still not satisfactory: the universal band is quite broad. The departure of our theoretical results from the Toburen rule can be easily explained by the fact that our atomic cross sections σ_α behave differently for each atom in terms of the projectile charges. By inspecting Figure 1, one can easily see that the rule $\sigma_\alpha/v_\alpha \sim \sigma_e$ is not well satisfied by the CDW. A much better general atomic rule is given by

$$\sigma_e^{\text{CDW}} = \frac{\sum_{\alpha} n_{\alpha} \sigma_{\alpha}^{\text{CDW}}}{\sum_{\alpha} n_{\alpha} v_{\alpha}^{\text{CDW}}}, \quad (5)$$

where

$$v_{\alpha}^{\text{CDW}} \sim \begin{cases} 4, & \text{for C, N, and O,} \\ 4.5, & \text{for P and S} \end{cases} \quad (6)$$

and, obviously, $v_H^{\text{CDW}} = 1$. The cross sections σ_e^{CDW} are plotted in Figure 5b. A much better sharp band is observed, especially at high energy, where the theory is expected to work. It will be interesting for experiments to tune up this theoretical prediction.

C. Emitted electron energies

In a given biological medium, direct ion ionization accounts for just a fraction of the overall damage. Secondary electrons, as well as recoil target ions, also contribute substantially to the total damage. We can consider the single differential cross section of the shell nl of the atom α , $d\sigma_{\alpha nl}/dE$, to be a function of the ejected electron energy E as a simple

distribution function [14]. Then, we can define the mean value \overline{E}_α as in Ref. [15],

$$\overline{E}_\alpha = \frac{\langle E_\alpha \rangle}{\langle 1 \rangle} = \frac{1}{\sigma_\alpha} \sum_{nl} \int dE E \frac{d\sigma_{\alpha,nl}}{dE}, \quad (7)$$

$$\langle 1 \rangle = \sigma_\alpha = \sum_{nl} \int dE \frac{d\sigma_{\alpha,nl}}{dE}, \quad (8)$$

where \sum_{nl} takes into account the sum of the different sub-shell contributions of the element α .

Figure 5 shows \overline{E}_i for six elements from Table I. The range of impact velocities was shorten up to $v = 10$ because of a numerical limitation in the spherical harmonics expansion. In our theoretical treatment, we expand our final continuum wave function as per usual,

$$\psi_{\vec{k}}^-(\vec{r}) = \sum_{l=0}^{l_{\max}} \sum_{m=-l}^l R_{kl}^-(r) Y_l^m(\hat{r}) Y_l^{m*}(\hat{k}). \quad (9)$$

We are confident with our calculations up to $l_{\max} \sim 30$. As the impact velocity v increases, so do $\langle E_\alpha \rangle$ and l_{\max} , which results in the inclusion of very oscillatory functions in the integrand. Furthermore, the integrand of $\langle E_\alpha \rangle$ includes the kinetic energy E (see Eq. (7), which cancels the small energy region and reinforces the large values, making the result more sensible to large angular momenta. Regardless, for $v > 10$, the first Born approximation holds.

In Figure 5, we estimate \overline{E}_α in the 0.5–2 a.u. velocity range, or equivalently from 15 to 50 eV, for all the targets. Our results agree with the experimental findings [14]. The dependence with the projectile charge Z is surprisingly sensible, which can duplicate the proton results. This effect can be attributed to the depletion caused by the multicharged ions to the yields of low energy electrons. In the high electron energy regime, the CDW falls on the simple first Born approximation, surviving the simple Z^2 law. Then, the ratio in Eq. (7) cancels out and \overline{E}_α becomes a universal value independent on Z .

Extending the simple stoichiometric model for the mean electron energy calculation, it results

$$\overline{E}_M = \frac{\sum_{\alpha} n_{\alpha} \overline{E}_{\alpha}}{\sum_{\alpha} n_{\alpha} \sigma_{\alpha}}. \quad (10)$$

For impact of H^+ and He^{2+} on water at 1 MeV/amu we obtain of $\overline{E}_{H_2O} = 43.7$ and 45 eV, while the experiments on liquid water Pimblott and LaVerne [16] found 51.5 and 52.2 eV, respectively. Just to stress the importance of the projectile charge, for O^{8+} on water at the same impact energy 1 MeV/amu we, obtain $\overline{E}_{H_2O} = 54.7$ eV, i.e. 25% larger than proton

impact. We recall here that there should not be any difference if the calculation is carried in first Born approximation. We will come back on this issue

D. Emitted electron angles

As mentioned before, secondary electrons contribute to the total damage. It is important not only the ejection energy but also the angle of emission. In similar fashion, we can consider the magnitude $d\sigma_{\alpha,nl}/d\Omega$ -i.e. the single differential cross section in terms of the ejected electron solid angle Ω - as a distribution function, and define the mean angle $\bar{\theta}_\alpha$ as

$$\bar{\theta}_\alpha = \frac{\langle \theta_\alpha \rangle}{\langle 1 \rangle} = \frac{1}{\sigma_\alpha} \sum_{nl} \int d\Omega \theta \frac{d\sigma_{\alpha,nl}}{d\Omega} \quad (11)$$

Figure 6 shows $\bar{\theta}_\alpha$ for our six elements of interest. Again here we observe an important dependence of $\bar{\theta}_\alpha$ with Z . It is the common view [21] that the angular dispersion of emitted electrons are nearly isotropic due to the fact that angular anisotropy of sub-50-eV yield is not significant. A typical used value of ejection angle is about $\bar{\theta}_\alpha \sim 70$ degrees [14] and this quite correct in the range of validity of the first Born approximation for any target. But when a distorted wave approximation is used as observed in Figure 6, $\bar{\theta}_\alpha$ decreases substantially with Z in the intermediate energy region. For example for C^{6+} impact the Bragg peak occurs at 0.3 MeV/amu where $\bar{\theta}_\alpha$ calculated in CDW is about the half of the one calculated with the First Born approximation. This correction should close the damage to the forward direction.

The only responsible of this correction is the capture to the continuum effect: the larger the charge Z the smaller $\bar{\theta}$ will be, of course at intermediate energies, not at high impact energies where the Born approximation rules. One illustrative observation is the behavior of antiprotons: the projectile in this case repels the electrons making the distribution almost symmetric. Note the opposite effect of proton and antiprotons, they run one oppose to the other one, as compared with the first Born approximation.

E. A modified stoichiometric model

One can correctly argue that the SSM considers an assembly of isolated neutral atoms which is definitively unrealistic. A first improvement is to consider that the atoms are not

neutral and within the molecule they have more or less electrons given by a charge q_α . One parameter that measures q_α is the Mulliken charge. This is not the only one, there is a large variety of charges such as the net or natural atomic charge [16], the lowin charge, etc.

Consider that the total amount of electrons Q_α on element α are equally distributed on all the atoms α , therefore each element α will have a an additional charge: $q_\alpha = Q_\alpha/n_\alpha$. positive or negative depending on the relative electronegative value respect to the other ones [17]. Instead of the integer number of elements n_α of the atom α , it could be argued that we have now an continuous number of atoms given by

$$n'_\alpha = n_\alpha - \frac{q_\alpha}{v_\alpha^{CDW}} \quad (12)$$

In the case of neutral atoms $q_\alpha = 0$, we obviously recover $n'_\alpha = n_\alpha$ as before.

To inspect the effect of the q_α we have run GAMES with the 6-31G basis set, including polarization functions for all the atoms. The calculations were carried out implementing the B3LYP functional [18, 19]. In Table (13) we display q_α of the different DNA basis and in the last column we rewrite the new stoichiometric expression.

Element	H	C	N	O	New stoichiometry
Adenine	+0.32	-0.55	+0.23		C _{4.92} H _{5.14} N _{4.77}
Thymine	+0.20	-0.54	+0.19	-0.52	C _{4.95} H _{6.13} N _{1.95} O _{2.13}
Cytosine	+0.28	-0.56	+0.21	-0.53	C _{3.93} H _{5.14} N _{2.79} O _{1.13}
Guanine	+0.46	-0.58	+0.20	-0.36	C _{4.89} H _{5.15} N _{4.80} O _{1.09}

(13)

All the previous formula holds with the simple replacement of integer value n_α by the continuous values n'_α to produce a new ionization cross section σ'

In Figure 7, we displays the relative difference of ionization cross sections

$$e = \frac{\sigma' - \sigma}{\sigma} \times 100 \quad (14)$$

for the four DNA basis. The difference is just very few percents. Indicating that the SSM is a quite robust model to treat the type of molecule we are dealing with, and of course within the range error that one can expect from the SSM.

We now return to the calculation of the mean electron energy of H^+ and He^{2+} in water \overline{E}_{H_2O} . If we consider that the residual charge of each hydrogen in water is $q_H = +0.35$ [17] which implies that on Oxygen we have a residual charge of $q_O = -0.7$, we could rewrite the formula of water using (14) as $H_{1.3}O_{1.17}$ considering $n_O^{CDW} \simeq 4$ and $n_H^{CDW} \simeq 1$.

Recalculating mean electron energy by impact of H^+ and He^{2+} on water at 1 MeV/amu we obtain: $\overline{E}_{H_2O} = 46.2$ and 47.6 eV which compared a little better with the experiments: 51.5 and 52.2 eV [20], respectively. i.e. within 10% of the experiments which is not bad accounting for the simplicity of our method.

Another parameter that we can calculate in our model is the fraction of energy carried by the electron f defined as

$$f = \frac{\sum_{\alpha} n_{\alpha} \sigma_{\alpha} \overline{E}_{\alpha}}{\sum_{\alpha} n_{\alpha} (\sigma_{\alpha} \overline{E}_{\alpha} + \sum_{nl} \sigma_{\alpha nl} E_{\alpha nl})} \quad (15)$$

Using our shell-to-shell ionization cross sections $\sigma_{\alpha nl}$ [7] and atomic binding energies of the atom α , $E_{\alpha nl}$ [?], we obtain $f = 0.70$ and 0.71 for H^+ and He^{2+} on water at 1 MeV/amu, which differ from the experiments $f = 0.81$ and 0.80, respectively.

This difference with the experiment could be attributed to the difference of binding energy between the molecular water 12.65 eV and the atomic component H (13.6 eV) and O (17.19 eV), which is an issue beyond our independent atom approximation and so our model cannot not accounted for. We could estimate this contribution resorting, once more to the stoichiometric, model, we can arrivesgar a upper-limit difference per molecule of water as

$$\delta E = (13.6 - 12.65)1.17 + (17.19 - 12.65)1.3 = 7 \text{ eV} \quad (16)$$

Most of this energy should be transfer to the kinetics energy of the emitted electron. Thus we can add 7 eV to the previous values to give $\overline{E}_{H_2O} = 53.2$ and 54.6 eV for H^+ and He^{2+} on water at 1 MeV/amu, respectively, much near to the experiments: 51.5 and 52.2 eV. If we add δE to the numerator of Eq.(15) we obtain $f = 0.81$ and 0.80 in perfect agreement with the experiments (see Table 1 of Ref.([20])

IV. CONCLUSIONS

We have calculated ionization cross sections by impact of antiprotons, H^+ , He^{2+} , Be^{4+} , C^{6+} , and O^{8+} with molecule involved in biological basis containing H, C, N, O, P and S with the CDW method. The importance of the influence of Z was observed in the mean energy \overline{E}_{α} and angle $\overline{\theta}_{\alpha}$. For a given target α , as Z increases \overline{E}_{α} increases but $\overline{\theta}_{\alpha}$ decreases. At high impact energy, say larger than 1 MeV/amu these values tend to the ones of the Born

approximation which embodies the simple Z^2 law. Sixteen molecules were investigated using the simple stoichiometric model. Results for the six DNA basis were presented and compared with the sparse available experiments. We explore the rule of Toburen which scales all the molecular ionization cross section when divided by the number of weakly bound valence electrons ν_α given by Eq.(2). We have found the rule scales much better when normalizing our theoretical ionization cross sections to the number ν'_α given by Eq.(6). And finally we attempt to improve the stoichiometric model by the use of the Mulliken charge to redefine a new stoichiometric model containing continuum rather than integer proportions. NO substantial correction was found indicating that the SSM works quite well.

Our aim in this article is to provide the tools to estimate any inelastic parameter parameter -such as the emission angle, the emitted mean energy and cross section- by the impact of any multicharged ion on any molecule containing H, C, N, O, P and S, with the help of the stoichiometrical model. Our goal was quite **pretencioso**, considering the simplicity of our proposal. However we think our results could be used to estimate the ionization magnitude with an acceptable level of uncertainties.

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