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http://dx.doi.org/doi:10.1063/1.5018401

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Cite as: J. Chem. Phys. 148, 021101 (2018); https://doi.org/10.1063/1.5018401
Submitted: 06 December 2017 . Accepted: 02 January 2018 . Published Online: 11 January 2018

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I. INTRODUCTION

Radiation-driven control of reactivity is a major goal in chemical physics/physical chemistry. This has been reported previously using ultrafast laser pulses,1 quantum molecular dynamics of photo-excited molecules,2 and coherent quantum manipulation.3 However these methods are not readily scalable for many potential technological or medical applications. Therefore, the achievement of electron-induced site- and bond-specific dissociation (on surfaces using STM tips4 and in the gas phase using low-energy electron beams5–9) in the mid 2000s was highly significant. The only previous control over dissociation pathways in atom-molecule collisions was demonstrated for potassium impact on gas-phase thymine and uracil.10 By achieving controlled dissociation of purines, the present experiments show that selective reactivity in charge transfer collisions is not restricted to the particular case of pyrimidine nucleobases. Indeed, we anticipate that this new route for controlled chemistry can be adapted for numerous collision systems.

As the most abundant secondary species produced by ionising radiation, low-energy electrons (defined here as <15 eV) are recognized as critically important reactive species in irradiated materials.11 In particular, dissociative electron attachment (DEA)12 and intermolecular charge transfer13 play key roles in radiation damage to DNA. These results have stimulated extensive experimental and theoretical research into low-energy electron interactions with gas-phase DNA/RNA constituents, revealing detailed understanding of their transient negative ion states.14 In aqueous conditions that evidently provide a closer approximation of biological environments,15 Wang et al.16 have shown that deoxyribonucleotides comprising adenine and guanine are more efficient at capturing pre-hydrated electrons than those comprising thymine and cytosine. Therefore, we expect electron-capture-induced reactive processes in the purine nucleobases to play a particularly important role in radiation-induced DNA damage.

In the present experiments, an alkali atom, potassium, is used as an electron donor to the nucleobase molecules, adenine and its derivatives. The donor-acceptor interaction changes from covalent (neutral) toionic at a particular distance, Rc,17 i.e., the crossing of the covalent and ionic diabatic states. For large potassium-molecule distances, the van der Waals and induction forces can be neglected and consequently the covalent potential is zero and the ionic potential is purely Coulombic (∝1/R). At infinite separation, the energy difference ΔE between the ionic and covalent configurations (the endoergicity of the electron transfer process), is given by IE(K)–EA(M), where IE(K) is the ionisation energy of the potassium atom and EA(M) is the electron affinity of the molecule. Rc is given by 14.41/ΔE (Å),18 where ΔE is expressed in eV. Taking the experimental vertical electron affinity of adenine as −0.54 eV19 (adiabatic value of 11 meV20), the value found for Rc is ~3.0 Å, meaning that the corresponding total cross sections for ion-pair formation (of the order of πRc2) is much larger (even one order of magnitude) than the corresponding gas kinetic cross sections.

Another relevant aspect pertaining significant differences between electron transfer and DEA experiments needs to be properly accounted for within the context of negative ion formation. Although the information gained in DEA experiments is relevant to assess which resonances may be involved in the attachment process, the role of a third body (K+1) in the vicinity of the temporary negative ion (TNI) is solely responsible to either shift or give access to other (diabatic) resonant states (i.e., in the K-M coordinate) probed in the collision

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Comparisons with electron scattering and DEA experiments are valuable when considering which temporary negative ion (TNI) states may be involved in collisional electron transfer. However, the presence of the electron donor (pre-transfer and post-transfer) can lead to major differences compared with DEA. These differences can be traced to shifting the energies of key orbitals in the neutral molecule and/or the TNI, as well as modifying TNI lifetimes with respect to electron autodetachment.  

II. EXPERIMENTAL SECTION

Negative ion mass spectra were obtained in a crossed beam setup consisting of a potassium source, an oven, and a time-of-flight (TOF) mass analyser. The components were housed in two high-vacuum chambers at a base pressure of 10^{-5} Pa. A neutral potassium beam generated from a charge exchange chamber intersected at right angles an effusive molecular beam consisting of the target molecules. Atomic K^+ ions, obtained from a potassium ionic source, were accelerated through a chamber containing potassium vapour where they resonantly charge exchanged to form a beam of fast neutral K fast atoms. The energy of the resultant K neutral beam was established by the initial acceleration of the K^+ ions and the geometry of the collimating slits in the charge exchange source. The lab-frame collision energy ranged from 15 to 100 eV, and the beam energy resolution at full width half maximum was 0.5 eV as measured with an energy loss analyser. The resulting neutral K beam entered a high vacuum chamber where it was monitored by an iridium surface ionisation detector operating in a temperature regime that only allows the detection of the fast beam. This sampled the beam intensity but did not interfere with the beam passing to the collision region. The biomolecular target beams were produced in a hot gas cell (oven) and admitted to vacuum by an effusive source through a 1-mm-diameter orifice where they were crossed with the
neutral hyperthermal potassium beam. The molecular oven was operated at a lower temperature (400 K measured by a platinum resistance probe) than previous experimental studies which reported no evidence for thermal decomposition of neutral adenine.\textsuperscript{19,23} The negative ions produced in the collision region were extracted by a 250 V/cm pulsed electrostatic field towards the entrance of the TOF where they were analysed and detected in single-pulse counting mode. In the present electron transfer experiments, the total energy available for anion excitation (the collision energy in the centre-of-mass frame minus the ionisation energy of potassium) varied from $\sim 6$ up to $\sim 68$ eV. Purine, adenine, 9-methyladenine, and 6-dimethyladenine were supplied by Sigma Aldrich with stated purities of 98\%, $\geq 99\%$, 97\%, and $\geq 98\%$, respectively, and adenine-2-d (adenine deuterated at the C2 position) was supplied by CDN Isotope Inc. with isotope enrichment of 97\%.

Experimental\textsuperscript{24,25} and theoretical\textsuperscript{26–28} studies of adenine’s tautomers have shown that the canonical form N(9)H dominates in the gas phase, while the N(7)H form is $\sim 33$ kJ/mol (0.342 eV) higher in energy.\textsuperscript{25,27,28}

### III. RESULTS AND DISCUSSION

Figure 1 shows the time-of-flight (TOF) mass spectra recorded at 100 eV lab frame collision energy of neutral potassium atoms with purine, adenine, 9-methyladenine, 6-dimethyladenine, and adenine-2-d (63.6, 65.5, 67.0, 68.3, and 65.6 eV available energy in the centre-of-mass, respectively). The TOF mass spectra show no evidence of parent anion formation ($M^-$), and this communication focuses on the dehydrogenated parent anion yield ($M–H$) only. ($M–H$) is produced from all five molecules where in 6-dimethyladenine, such yield is barely visible above background noise in the present measurements.

Adenine branching ratios (not shown here) reveal that loss of a neutral H atom is a precursor in the formation of other fragment anions. Such is discernible in Fig. 2 (15 eV lab frame collision energy) where ($M–H$) dominates for the case of adenine and 6-dimethyladenine. The threshold for electron transfer (IE(K)–EA(M) $\approx 4$ eV) is smaller than the collision energy, so the molecular anion can be formed with an excess of internal energy. For the molecular compounds...
investigated here, 6-dimethyladenine exhibits the highest number of degrees of freedom (57 modes), among which the excess energy can be redistributed resulting in fragmentation (100 eV lab frame). However, if the lifetime of the metastable anion is long enough, intramolecular energy redistribution may occur competing with direct dissociation. Such is the dominant case of longer collision times as revealed in the TOF mass spectra in Fig. 2.

Clearly, all of the conceivable H loss reaction pathways [from the N9, C8, C6, and C2 sites of purine and from the N9, C8, (NH₂)C6, and C2 sites of adenine] are energetically accessible at the relatively high lab frame collision energy of 100 eV. However, the absence of an (M–D)⁻ signal in the measurement on partially deuterated adenine indicates that hydrogen loss from the C2 position on adenine can be ruled out. This may be rationalised in terms of strong autodetachment competing with dissociation for this specific channel. It is also interesting to consider the present results in the context of previously calculated electrostatic potential maps and isodensity maps of the lowest virtual ω⁻ molecular orbitals at the B3LYP/aug-cc-pVTZ level for purine, adenine, and 6-dimethyladenine. Therefore there is great potential in the future to identify many more charge transfer collisions that can initiate selective reactivity of the kind demonstrated here, extending to tailored chemical control for industrial and even medical applications.

IV. CONCLUSION

We show here that selective hydrogen removal from the adenine molecule can be achieved in collisional charge transfer experiments by tuning the collision energy. It is striking that such fine control over reactivity can be achieved in an energetic collision between an atom and a relatively complex molecule with numerous competing relaxation pathways. Indeed, the observed selectivity cannot be explained solely in terms of the threshold energies required to break specific bonds in the temporary negative ion. On the contrary, it reflects the specific dynamics of the three-body interaction involving the molecule, the transferred electron, and the donor atom. Considerable progress has been made in recent years towards understanding these complex dynamics both experimentally and via ab initio calculations. Therefore there is great potential in the future to identify many more charge transfer collisions that can initiate selective reactivity of the kind demonstrated here, extending to tailored chemical control for industrial and even medical applications.

ACKNOWLEDGMENTS

T.C., M.M., and F.F.S. acknowledge the Portuguese National Funding Agency FCT-MCTES through No. SFRH/BD/52538/2014, PD/BD/106038/2015, and researcher position No. IF-FCT/IF/00380/2014, respectively, and together with PLV the research Grant No. UID/FIS/00068/2013. This work was also supported by Radiation Biology and Biophysics Doctoral Training Programme (RaBBIIT, No. PD/00193/2010); No. UID/Multi/04378/2013 (UCIBIO). GG acknowledges partial financial support from the Spanish Ministry of Economy, Industry and Competitiveness (Project No. FIS2016-80440). S.E. acknowledges support from the British EPSRC through a Career Acceleration Fellowship (No. EP/J002577/1).