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open-cage iminium ions†

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The protonated form of amantadine (1- $C_{10}H_{15}NH_2$, Ama), the amino derivative of adamantane ($C_{10}H_{16}$, Ada), is a wide-spread antiviral and anti-Parkinsonian drug and plays a key role in many pharmaceutical processes. Recent studies reveal that the adamantyl cage $(C_{10}H_{15})$ of Ama can open upon ionization leading to distonic bicyclic iminium isomers, in addition to the canonical nascent Ama+ isomer. Herein, we study protonation of Ama using infrared photodissociation spectroscopy (IRPD) of Ar-tagged ions and density functional theory calculations to characterize cage and open-cage isomers of AmaH⁺ and the influence of the electron-donating NH2 group on the cage-opening reaction potential. In addition to the canonical ammonium isomer (AmaH $^+$ (I)) with an intact adamantyl cage, we identify at least one slightly less stable protonated bicyclic iminium ion (Ama $H^+(II)$). While the ammonium ion is generated by protonation of the basic NH_2 group, $AmaH^+(II)$ is formally formed by H addition to a distonic bicyclic iminium ion produced upon ionization of Ama and subsequent cage opening.

Infrared spectra and structures of protonated

amantadine isomers: detection of ammonium and

Introduction

Amantadine (Ama, 1-tricyclo[3.3.1.1^{3,7}]decylamine, 1-adamantylamine, 1-aminoadamantane, C₁₆H₁₅NH₂) is the amino derivative of adamantane (C₁₀H₁₆, Ada), the parent molecule of the group of diamondoids.1 These nm-sized H-passivated nanodiamonds are rigid, stress-free, and highly stable cycloalkanes and form a fundamental class of saturated sp3-hybridized hydrocarbon molecules, 2-4 with (potential) applications in a wide range of disciplines including materials science, molecular electronics, medical sciences, chemical synthesis, and astrochemistry. 5-17 For example, radical cations of diamondoids are predicted to be intermediates in substitution reactions in polar solvents. 14,18-21 Based on the detection of several amines²² and protonated molecules²²⁻²⁴ in the interstellar medium and the likely presence of diamondoids,22 the occurrence of Ama and its protonated form is also expected. 13,25,26

Amantadine, particularly in its N-protonated form, belongs to the most important diamondoid derivatives, because of its use in pharmaceutical applications as antiviral and anti-Parkinsonian drug. It is successfully marketed under several brand names, including Symmetrel® (Ama·HCl), Gocovri®, Symadine[®], and Osmolex ER[®]. ^{15,27-30} In all postulated mechanisms,

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N-protonated Ama (or its dimethylated derivative memantine, Namenda[®]) is the biochemically active species.^{31,32} Ama is effective in the prophylaxis and treatment of influenza A infections by preventing the virus from entering the host cell through blocking of the ion channel.³³⁻³⁵ However, due to drug resistance, its use is no longer recommended for influenza. 36,37 Although the mechanism of action against Parkinsonism is not yet fully understood, the drug enhances the release of dopamine from nerve endings of brain cells, along with stimulating the norepinephrine response.38-40 In addition to its pharmaceutical use, Ama has antagonistic effects on NMDA (N-methyl-D-aspartate) receptors 41,42 and is discussed for treating other diseases such as multiple sclerosis, depression, and cocaine addiction. 43-45 In 2013, memantine was in the top 100 best-selling drugs worldwide, with sales exceeding \$109.46

In addition to its pharmaceutical use, the diamondoid derivative Ama is also of interest for studying ionizationinduced rearrangement processes of the adamantyl cage. 47,48 By replacing H with the electron-donating NH2 group at the apical 1-position, 42,49 the chemical properties of diamond-like structures are mostly retained but the barrier to cage opening is strongly reduced. 47,48 The geometric, vibrational, and electronic properties of Ama are well-known from infrared (IR), Raman, and electron momentum spectroscopy. 50-54 Lowresolution electron momentum spectra show that ionization of Ama to the electronic ground state of the cation occurs by electron ejection from the nonbonding N lone pair of the NH₂ group (HOMO), with a rough estimate of the vertical ionization

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energy of 8.6 eV.⁵³ In our recent IR spectroscopic and quantum chemical studies of Ama⁺L_n clusters (with L = Ar, N₂, $\mathrm{H}_{2}\mathrm{O}$), 47,48,55 we identified, in addition to the canonical nascent $Ama^+(I)$ isomer with an intact $C_{10}H_{15}$ cage, two distonic bicyclic iminium isomers Ama⁺(II) and Ama⁺(III) in which the adamantyl cage opens upon ionization. H → NH₂ substitution drastically lowers all barriers for the rearrangement processes, because of the strongly p/ π -electron donating character of the NH₂ group, which leads to high and thus detectable yields for the formation of Ama⁺(II) and Ama⁺(III). Starting from the cage structure Ama⁺(I) produced by vertical ionization of Ama (E_0 = 46 kJ mol⁻¹), C-C bond activation opens the adamantyl cage forming the primary radical Ama⁺(II) $(E_0 = 87 \text{ kJ mol}^{-1}) \text{ via a}$ boat → chair conversion of one of the cyclohexane rings. In a subsequent 1,2 H-shift accompanied by chair → boat back conversion, the much more stable tertiary radical Ama+(III) is generated ($E_0 = 0 \text{ kJ mol}^{-1}$). Interestingly, no open-cage isomers were detected in previous IR and optical spectra of Ada⁺ and its clusters generated in the same type of ion source due to ionization from a different orbital and higher reaction barriers. 26,56,57 Instead of ionization of Ama, we characterize herein the effects of protonation using the same IR spectroscopic and quantum chemical tools to determine the structure of protonated amantadine, the impact of the electronwithdrawing NH₃⁺ group on the adamantyl cage of AmaH⁺, and the possible formation of open-cage isomers. Experimentally, we apply IR photodissociation (IRPD) spectroscopy to mass-selected Ar-tagged AmaH⁺ ions, whereby the weaklybonded Ar ligand has essentially no impact on the structural, energetic, vibrational, and chemical properties of AmaH⁺, as recently demonstrated for the Ama⁺ radical cation. ^{47,48} Despite its high pharmaceutical importance, no spectroscopic studies are available for isolated AmaH⁺. Mass spectrometry experiments provide information about its fragmentation and proton affinity.58 Several spectrophotometric, NMR and IR studies of the amantadine hydrochloride salt (Ama·HCl) focus mostly on analytical applications of this drug molecule. 54,59-62

2. Experimental and computational techniques

IRPD spectra of AmaH⁺Ar are recorded in a quadrupole-octupolequadrupole tandem mass spectrometer coupled to an electron ionization source described elsewhere. 63,64 The clusters are produced in a pulsed supersonic plasma expansion by electron and/ or chemical ionization (EI/CI) close to the nozzle orifice followed by clustering reactions. The expanding gas mixture is generated by passing a carrier gas mixture of 5% H₂/He and Ar in the ratio of 1:50 through a heated reservoir containing Ama (Sigma Aldrich, >97%, $T \sim 130^{\circ}$) at a stagnation pressure of 5-9 bar. The filaments of the EI source are operated with an offset voltage of 220 V, which determines the upper limit for the kinetic energy of the electrons hitting the molecules in the expansion. A typical mass spectrum of the ion source is shown in the electronic supporting information (Fig. S1, ESI†). One possible production

route for AmaH⁺Ar involves EI of H₂ (eqn (1)) followed by exothermic proton transfer reactions (eqn (2) and (3)) to generate AmaH⁺ and three-body collisions to form the AmaH⁺Ar clusters (eqn (4)):65,66

$$H_2 + e \rightarrow H_2^+ + 2e$$
 (1)

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$
 (2)

$$Ama + H_3^+ \rightarrow AmaH^+ + H_2 \tag{3}$$

$$AmaH^{+} + Ar + M \rightarrow AmaH^{+}Ar + M$$
 (4)

Reaction (3) is highly exothermic (by 557 kJ mol^{-1} at the B3LYP-D3/cc-pVTZ level) and thus may lead to opening of the adamantyl cage. An alternative route for the formation of AmaH⁺ involves EI/CI of Ama to form the Ama⁺ radical cation (eqn (5)), which then reacts with H₂ to generate AmaH⁺ (eqn (6)):

$$Ama + e \rightarrow Ama^{+} + 2e \tag{5}$$

$$Ama^{+} + H_{2} \rightarrow AmaH^{+} + H \tag{6}$$

As has been demonstrated recently, reaction (5) can lead to cage opening and subsequent 1,2 H-shift, thereby producing three structural isomers of Ama+, including the canonical cage structure (Ama⁺(I)), and two bicyclic distonic iminium ions (Ama⁺(II) and Ama⁺(III)), with primary and tertiary radical centers.⁴⁷ While Ama+(I) will preferentially hydrogenate at the NH2 group in reaction (6) leading to an ammonium cation, Ama+(II) and Ama⁺(III) will hydrogenate at the radical centers and thus form iminium cations.⁶⁷ Although reaction (6) is endothermic (by 74 kJ mol⁻¹ for isomer **III** at the B3LYP-D3/cc-pVTZ level), there may be enough energy available in form of internal energy left in Ama^{+} from reaction (5).

Collision-induced dissociation (CID) experiments are performed to confirm the chemical composition of the produced AmaH⁺Ar clusters (Fig. S2, ESI[†]). The generated AmaH⁺Ar clusters are mass-selected in the first quadrupole and irradiated in an adjacent octupole ion guide with a tuneable IR laser pulse (ν_{IR}) emitted from an optical parametric oscillator pumped by a nanosecond Q-switched Nd:YAG laser. The IR radiation is characterized by 10 Hz repetition rate, <4 cm⁻¹ bandwidth, and pulse energies of 2-5 mJ and 0.1-0.5 mJ in the XH stretch (2600-3700 cm⁻¹) and fingerprint ranges (1100-1900 cm⁻¹). Frequency calibration to better than 1 cm⁻¹ is performed using a wavemeter. Resonant vibrational excitation of the clusters leads exclusively to the loss of Ar. The AmaH⁺ fragment ions are selected by the second quadrupole and monitored by a Daly detector as a function of the laser frequency to obtain the IRPD spectra of AmaH+Ar. Separation of laserinduced dissociation from metastable decay background is achieved by triggering the ion source at twice the repetition rate of the laser and subtracting the signals from alternating triggers. All IRPD spectra are normalized for frequency-dependent variations in the photon flux.

Geometric, vibrational, energetic, and electronic properties of Ama, AmaH⁺, and AmaH⁺Ar in their electronic ground states are characterized by quantum chemical calculations at the dispersion-corrected B3LYP-D3/cc-pVTZ level. 68 This computational

approach has already provided reliable results for Ama⁺L_n clusters and is an efficient compromise between accuracy and computing time. 47,55,56 Relative energies and equilibrium binding energies (Ee, De) are corrected for harmonic zeropoint vibrational energy to yield E_0 and D_0 . To compensate for the different anharmonicity of the various CH/NH stretch and fingerprint modes, three different scaling factors are employed (0.9732, 0.9618, and 0.9491 for fingerprint and CH and NH stretch modes).55 Computed IR stick spectra are convoluted with Gaussian line profiles (fwhm = 10 cm⁻¹) to facilitate convenient comparison with the measured IRPD spectra. Natural bond orbital (NBO) analysis is employed to evaluate the atomic charge distributions. ^{69,70} We only consider singlet electronic states, because triplets are computed to be very high in energy ($E_0 \ge 350 \text{ kJ mol}^{-1}$). Cartesian coordinates

and energies of all relevant structures are available in the ESI.†

3. Experimental results

Typical mass spectra of the EI source show the parent Ama⁺ radical cation (m/z 151), its dehydrogenated and protonated closed-shell ions ([Ama-H]⁺/AmaH⁺ at m/z 150/152), and their clusters with Ar, N2 and H2O (Fig. S1, ESI†). Clusters with H2O appear because traces of H2O have been added to the gas inlet system for parallel experiments on AmaH⁺(H₂O)_n clusters. In addition, intense fragment ions of Ama⁺ (F⁺ at m/z 135, 108, 94, 57) are detected, consistent with the standard EI mass spectrum of Ama, confirming the identity of m/z 151 as Ama⁺ (Fig. S1, ESI \dagger). ^{54,71–73} Note that the standard EI mass spectrum of Ama is quite different from that of Ada, indicating the strong impact of the NH2 group on the fragmentation process of the adamantyl cage.⁵⁴ One of the most intense peaks in the mass spectrum of the EI source (m/z 135) reveals the loss of NH₃ from AmaH⁺,⁵⁸ most likely arising from fragmentation of N-protonated AmaH⁺ into the very stable 1-adamantyl cation.⁵⁸ Further fragmentation of m/z 135 down to m/z 93 by elimination of C₃H₆ is only weakly observed, ⁵⁸ possibly an indication for soft N-protonation of Ama. The CID spectrum of AmaH⁺Ar shows merely the loss of Ar, so that any significant isobaric mass contamination can be excluded (Fig. S2, ESI†).

The IRPD spectrum of AmaH⁺Ar recorded in the fingerprint (1100-1900 cm⁻¹) and XH stretch ranges (2700-3700 cm⁻¹) is shown in Fig. 1. The positions and widths of the transitions observed are listed in Table 1, along with the proposed vibrational and isomer assignments derived from the B3LYP-D3 calculations. The fingerprint range covers CH_2 torsion (τ_{CH_2}) and wagging (γ_{CH_2}) modes (A–D), and CH₂/NH_n bending ($\beta_{\text{CH}_2/\text{NH}_n}$) and CN stretching $(\nu_{\rm CN})$ fundamentals (E-I). The XH stretch range probes aliphatic CH_n stretch modes (ν_{CH_n}) of the Ama⁺ moiety (**J-N**), overtone and combinations bands of $\beta_{\rm NH_{2/3}}$ and $\nu_{\rm CN}$ fundamentals (O, P, T), and symmetric and antisymmetric $\left(\nu_{\mathrm{NH}_{2/3}}^{\mathrm{s/a}}\right)$ NH stretch modes of the NH_2^+ (S, U) and NH_3^+ groups (Q, R).

To our initial surprise, we observe five bands in the NH stretch range (Q-U) and not just two, which one would expect for Ama protonated at the basic NH2 group. The resulting

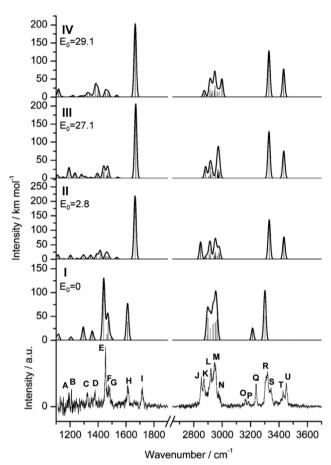


Fig. 1 IRPD spectra of AmaH⁺Ar in the XH stretch and fingerprint ranges compared to linear IR absorption spectra of Ama+(I-IV) calculated at the B3LYP-D3/cc-pVTZ level (Tables S1 and S2, ESI†). The positions of the transitions observed (A-U) and their vibrational and isomer assignment are listed in Table 1. Relative energies (E_0) are given in kJ mol⁻¹.

ammonium ion of AmaH+ with C3v symmetry (RNH3+) has symmetric (a) and doubly degenerate antisymmetric (e) NH stretch modes, whereby the latter may split into two components upon Ar-tagging at the NH₃⁺ group. By comparison with NH₄⁺ and protonated aniline (AnH⁺) and their complexes with rare gas atoms, 67,74 the $\nu_{\rm NH_2}$ modes of the RNH₃⁺ are expected in the 3150-3400 cm⁻¹ range and may thus be associated with bands Q, R, and possibly S, observed at 3238, 3317, and 3344 cm⁻¹. On the other hand, $\nu_{\rm NH_2}$ modes of amine cations (RNH₂⁺), such as the NH₃⁺, An⁺, and the carbenium isomers of AnH⁺,^{67,75–77} have their NH stretch frequencies toward higher frequency (3350-3500 cm⁻¹), and such isomers of AmaH⁺ may thus account for bands U, T, and possibly S observed at 3451, 3428, and 3344 cm⁻¹. Hence, the various intense NH stretch bands suggest the presence of at least two AmaH⁺ isomers, one expected ammonium ion and one unexpected iminium ion. The larger width of R and its shoulder S may arise from effects of Ar-tagging, giving rise to a splitting upon symmetry reduction and minor shifts upon formation of NH···Ar hydrogen bonds (H-bonds). However, Ar-tagging of a single AmaH⁺ isomer alone cannot account for the rich observed NH stretch spectrum with its large frequency spread.

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Table 1 Positions, widths (fwhm in parenthesis) and vibrational and isomer assignments of the transitions observed in the IRPD spectrum of AmaH+Ar (Fig. 1)

Peak	Mode	AmaH ⁺ Ar	Isomer
A	$ au_{\mathrm{CH}_2}$	1187 (12)	$\mathbf{I},\mathbf{II}_{.}^{b}$
В	$ au_{\mathrm{CH}_2}^{2}$	1209 (2)	$\mathbf{I}, \mathbf{II}^{b}$
C	$\gamma_{\rm CH_2}$, $\tau_{\rm CH_2}$	1322 (8)	$\mathbf{I}, \mathbf{II}^{b}$
D	γ_{CH_2} , τ_{CH_2}	1377 (Ì1)	$\mathbf{I}, \mathbf{II}^b$
E	$\gamma_{\rm NH_3(umbrella)}, \beta_{\rm CH_2}$	1453 (13)	$\mathbf{I}^{\acute{b}}$
F	β_{CH_2}	1474 (6)	$\mathbf{I}, \mathbf{II}^b$
G	β_{CH_2} , β_{CH_3}	1483 (5)	$\mathbf{I}, \mathbf{II}^b$
Н	β_{NH_3}	1611 (12)	ľ
I	β_{NH_2}	1714 (15)	\mathbf{II}^b
J	ν_{CH_n}	2853 (10)	II
K	ν_{CH_n}	2872 (7)	\mathbf{II}^b
L	ν_{CH_n}	2921 (14)	$\mathbf{I}, \mathbf{II}_{\cdot}^{b}$
M	ν_{CH_n}	2949 (17)	$\mathbf{I}^{'}_{oldsymbol{,}}\mathbf{II}^{b}$
N	ν_{CH_n}	2973 (5)	\mathbf{H}^{b}
0	$2\beta_{\mathrm{NH}_{3}}^{\mathrm{CH}_{n}}$	3164 (7)	I
P	$2\beta_{\mathrm{NH}_{3}}^{\mathrm{NH}_{3}}$	3185 (5)	I
Q	$ u_{\mathrm{NH}_{3}}^{\mathrm{S}} $	3238 (13)	I
R	$ u_{\mathrm{NH}_{3}}^{\mathrm{a}}$	3317 (21)	I
S	$ u_{\mathrm{NH}_{2}}^{\mathrm{s}}$	3344 (7)	\mathbf{II}^b
Т	$2eta_{\mathrm{NH}_{2}}$	3428 (11)	\mathbf{II}^b
U	$ u_{\mathrm{NH}_2}^{\mathrm{a}} $	3451 (10)	\mathbf{H}^{b}

^a All values are given in cm⁻¹. ^b Could be also assigned to the less stable isomers III and IV.

Similar to Ama+Ar,47 the aliphatic CH stretch range of AmaH⁺Ar (2800-3000 cm⁻¹) exhibits several bands (J-N), with two strong broader features L and M (2921 and 2949 cm⁻¹), one weak peak N in the blue shoulder of M (2973 cm $^{-1}$), and two low-frequency bands I and K with medium intensity (2853 and 2872 cm⁻¹). The two very weak bands O and P (3164 and 3185 cm⁻¹) between the CH and NH stretch ranges are probably overtones or combinations bands of $\beta_{NH_{3/2}}$ bend modes.

The fingerprint range is dominated by a very intense narrow band E at 1453 cm⁻¹, accompanied by two weaker sharp peaks F and G (1474 and 1483 cm⁻¹) in its blue shoulder. Interestingly, two broader and possibly unresolved features H and I at 1611 and 1714 cm⁻¹ with comparable medium intensity occur in the NH_{2/3} bending range, confirming the conclusion of the presence of (at least) two isomers drawn from the NH stretch range. Furthermore, one weak transition A (1187 cm⁻¹), one sharp peak B (1209 cm⁻¹), and two bands C and D with similar intensity (1322 and 1377 cm⁻¹) occur in the range of $\beta_{\rm CH}$, $\gamma_{\rm CH}$, $\tau_{\rm CH_2}$, and $\rho_{\rm NH_2}$.

In addition to the AmaH⁺Ar dimer (n = 1), we have also recorded the IRPD spectra of AmaH $^{+}$ Ar_n with n = 2 and 3 in the XH stretch range. Similar to the case of Ama⁺Ar_n, ⁴⁸ the incremental spectral shifts and splittings upon tagging with further Ar ligands are very small and do not provide any additional information about the vibrational and isomer assignment. Hence, we do not discuss them in detail further here. The major information extracted from these IRPD spectra concerns the binding energy of the Ar ligands. The IRPD signal of AmaH⁺Ar₃ is observed exclusively in the AmaH⁺ monomer fragment channel, providing a rough upper limit of 1000 cm⁻¹ for the Ar binding energy, fully consistent with the results of the B3LYP-D3 calculations detailed in Section 4.

4. Computational results and discussion

4.1. AmaH⁺ isomers I–IV

Starting from neutral Ama and the previously detected Ama+ radical cation isomers (Fig. S3, ESI†), stable structures of AmaH⁺ are constructed by adding a proton to the basic NH₂ group of Ama or a H atom to the C radical centers of the opencage Ama+ isomers. Protonation of Ama at C is energetically highly unfavourable (when retaining the cage), because it would result in a fivefold coordinated C atom of the cycloalkane. The resulting AmaH⁺ isomers I-IV are shown in Fig. 2, and their corresponding IR spectra are compared in Fig. 1 to the IRPD spectrum measured for AmaH⁺Ar (Table S1, ESI[†]). All relevant energies are listed in Table S2 (ESI†).

In the electronic ground state of neutral Ama (${}^{1}A_{1}$, C_{s}), the NH₂ group is attached in a pyramidal configuration (sp³ hybridisation of N) to the C₁₀H₁₅ cage via a C-N single bond $(r_{\rm CN} = 1.467 \text{ Å})$. The N-H bonds are relatively short $(r_{\rm NH} = 1.015 \text{ Å})$, leading to high-frequency symmetric and antisymmetric NH

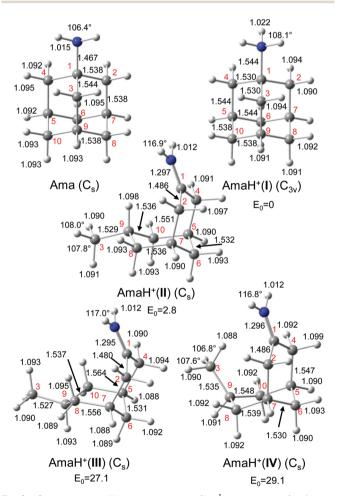


Fig. 2 Calculated equilibrium structures (in Å and degrees) of Ama and AmaH⁺(I-IV) in their ground electronic state (B3LYP-D3/cc-pVTZ), along with numbering of the C atoms (in red). Relative energies (E_0) are given in kJ mol-1.

stretch modes $\left(\nu_{\text{NH}_2}^{\text{s/a}} = 3285/3359 \text{ cm}^{-1}\right)$, with very low IR oscillator strength (3/0.2 km mol⁻¹). In general, the calculated structure and IR spectrum of Ama agree well with previous experimental and computational data. 51-54 Protonation of Ama at the NH₂ group produces the ammonium isomer I of AmaH⁺ with C_{3v} symmetry in the ¹A₁ electronic ground state, with a computed proton affinity (PA = 957 kJ mol⁻¹) in close agreement with the experimental value (PA = 949 kJ mol^{-1}). This structure is indeed the global minimum on the AmaH $^+$ potential (E_0 = 0 kJ mol⁻¹). N-Protonation of Ama causes a drastic elongation of the N-H bonds by 7 mÅ to 1.022 Å and a slight increase in the NH₂ angle to 108.1°, while preserving the pyramidal configuration. The former effect results in massive $\nu_{\rm NH}$ red shifts of $\sim 70/60~{\rm cm}^{-1}$ $(\nu_{\rm NH_{2/3}}^{\rm s}=3285~{\rm vs.}~3214~{\rm cm}^{-1},\,\nu_{\rm NH_{2/3}}^{\rm a}=3359~{\rm vs.}~3301~{\rm cm}^{-1},\,{\rm Fig.}~{\rm S4}$ and Table S3, ESI†). Moreover, the IR intensities of $\nu_{\mathrm{NH_{3}}}$ are drastically enhanced (by a factor $\sim 10/500$) due to the increased charge on the NH protons $(q_H = 0.429 e)$ and thus can readily be detected by IRPD. However, the increase in IR activity is smaller than for Ama⁺ (factor $\sim 100/350$), for which the $\nu_{\rm NH_2}$ modes are blue-shifted compared to Ama (Table S4, ESI†). Furthermore, the formation of the third N-H bond produces an additional intense $\gamma_{\rm NH_3}$ umbrella inversion mode at 1441 cm⁻¹ ($I_{\gamma \rm NH_3}$ = 130 km mol⁻¹), which is typical for NH_3^+ groups.⁷⁹ The degenerate β_{NH_3} modes $(\beta_{\rm NH_3}$ = 1611 cm $^{-1},$ $I_{\beta_{\rm NH_3}}$ = 39 km $\rm \,mol^{-1})$ have almost the same frequency and intensity as the β_{NH_2} mode of Ama (β_{NH_2} = 1609 cm⁻¹, $I_{\beta_{\rm NH2}}$ = 34 km mol⁻¹). In contrast to ionization of Ama, protonation lengthens the C-N single bond by 77 mÅ to 1.544 Å and shortens the adjacent C-C bonds ($r_{C1C2} = 1.530 \text{ vs.}$ 1.538 Å, r_{C1C3} = 1.530 vs. 1.544 Å), which is due to the higher positive charge on the NH_3^+ group $(q_{NH_3} = 0.605 \ e)$ and its electronwithdrawing character. Moreover, the C-C bonds parallel to the C_3 symmetry axis are slightly elongated compared to Ama ($r_{C4C5} = 1.544$ vs. 1.538 Å). Almost all C-H bonds contract slightly ($\Delta r_{\rm CH} = 2$ mÅ) resulting in blue shifts of the $\nu_{\rm CH}$ bands ($\nu_{\rm CH}$ = 2890 vs. 2899 cm⁻¹, $\nu_{\rm CH}$ = 2917 vs. 2956 cm⁻¹). The highest occupied molecular orbital (HOMO) has CC σ character and extends over the whole adamantyl

The AmaH⁺(II) isomer (1 A', C_{s} , $E_{0} = 3.0 \text{ kJ mol}^{-1}$) is almost isoenergetic with the global minimum and formally derived from the open-cage Ama⁺(III) radical cation isomer by adding a H atom at its tertiary C9 radical center. As shown recently, ionization of Ama can trigger a rearrangement reaction, producing via cage opening and subsequent 1,2 H-shift the bicyclic distonic Ama⁺(III) iminium radical cation (involving a barrier of V_b = 123 kJ mol⁻¹), whose C9 radical center is a good acceptor for a H radical. 47,48 Consequently, AmaH $^{+}$ (II) has also an open-cage structure with one CH3 group (C3H3) and a C9H group with its C-H bond oriented toward the nearly planar CNH₂⁺ group (r_{C9H} ...C1 = 2.450 Å). As a result, the cage opens much more than for Ama $^+$ (III) $(\theta_{\text{C1C9C3}} = 155.3^{\circ} \text{ vs. } 106.1^{\circ}, r_{\text{C1}\cdots\text{C3}} = 4.47 \text{ vs. } 3.35 \text{ Å}),^{47} \text{ and the C-C}$ bonds at the former C9 radical center drastically elongate ($r_{C3C9} =$ 1.482 vs. 1.529 Å, $r_{C9C8} = 1.492$ vs. 1.536 Å). Moreover, the C2-C7/ C4-C5 bonds are slightly stretched by 9 mÅ to 1.551 Å, whereas the remaining C–C bonds contract (r_{C1C2} = 1.491 vs. 1.486 Å, r_{C5C6} = 1.537 vs. 1.532 Å, $r_{C7C8} = 1.543$ vs. 1.536 Å). The cyclohexane ring

cage, while it has no amplitude at the NH₃⁺ group (Fig. S5, ESI†).

carrying the NH₂⁺ group has chair configuration as in Ama⁺(III) and AmaH⁺(I). The C-H bonds of the C atoms adjacent to C9 contract $(\Delta r_{\rm CH} = 4-8 \text{ mÅ})$, while most of the other C-H bonds elongate $(\Delta r_{\rm CH} = 1-2 \text{ mÅ})$. The newly formed C9–H bond is the longest bond $(r_{\rm CH}$ = 1.098 Å), which produces an intense $\nu_{\rm CH}$ mode $(\nu_{\rm CH}$ = 2848 cm⁻¹) significantly red-shifted from the other $\nu_{\text{CH}_{a}}$ modes. It may thus serve as indicator for this isomer. The N-H bonds of the planar CNH₂⁺ group (sp² hybridization of N) of the iminium ion are stretched by 3 mÅ to 1.012 Å, while the NH₂ bond angle remains almost the same ($\Delta\theta_{\rm NH_2} = 0.1^{\circ}$), resulting in a blue shift of $\nu_{\rm NH_2}^{\rm s}$ $(\nu_{\rm NH_2}^{\rm s}=3331~\rm vs.~3358~\rm cm^{-1})$ and a slight red shift of $\nu_{\rm NH_2}^{\rm a}$ $(\nu_{\rm NH_2}^{\rm a} = 3435 \text{ vs. } 3433 \text{ cm}^{-1}) \text{ compared to Ama}^{+}(\mathbf{III}).^{47} \text{ However,}$ the N-H bonds in AmaH $^+$ (II) are much shorter than in AmaH $^+$ (I), so that its NH₂ modes are well separated from the NH₃ modes ($\Delta\nu_{\rm NH}$ $\sim 100 \text{ cm}^{-1}$). As with Ama⁺(III), ⁴⁷ a C=N double bond is present in AmaH⁺(II), whose ν_{CN} mode couples with β_{NH_2} , resulting in a weak $\nu_{\rm CN}$ band at 1534 cm⁻¹ and an intense $\beta_{\rm NH}$ band at 1664 cm⁻¹. Compared to Ama⁺(III), however, the C=N double bond is much shorter in AmaH+(II), which leads to blue shifts in both $\beta_{\rm NH_2}$ and $\nu_{\rm CN}$ by 34 and 23 cm⁻¹, respectively. Similar to $\text{Ama}^+(\text{III}) (q_{\text{CNH}_2} = 0.608 \, e)$, most of the positive charge in $\text{AmaH}^+(\text{II})$ is located at the CNH_2^+ group $(q_{CNH_2} = 0.748 \ e)$ and the HOMO is localized over the adamantyl framework (Fig. S5, ESI†).

The significantly less stable AmaH⁺(III) iminium isomer $(^{1}A', C_{s}, E_{0} = 27.4 \text{ kJ mol}^{-1})$ has a similar open-cage structure as AmaH⁺(II), with one NH₂⁺ and one CH₃ group but the C9-H bond pointing away from the CNH2+ group. The cage is less open than in AmaH⁺(II) ($\theta_{C1C9C3} = 124.6^{\circ} \text{ vs. } 155.3^{\circ}, r_{C1\cdots C3} =$ 4.69 vs. 4.47 Å), and the second cyclohexane ring changes from chair to boat configuration. AmaH+(III) can be formed by adding a H atom to either the primary C3 radical center of Ama⁺(II) or the tertiary C9 radical center of Ama⁺(III). The C2-C7/C4-C5 bonds and the C7-C8/C5-C10 bonds are elongated compared to AmaH⁺(II) ($r_{C2C7} = 1.564 \text{ vs.} 1.552 \text{ Å}, r_{C7C8} = 1.556 \text{ vs.}$ 1.536 Å), while the remaining C-C bonds differ only slightly $(r_{\rm C1C4} = 1.480 \text{ vs.} 1.486 \text{ Å}, r_{\rm C5C6} = 1.531 \text{ vs. } 1.532 \text{ Å}, r_{\rm C8C9} = 1.537$ vs. 1.537 Å, $r_{\text{C3C9}} = 1.527 \text{ vs. } 1.529 \text{ Å}$). Compared to AmaH⁺(II), most C-H bonds contract only slightly ($\Delta r_{\rm CH} = 1-2$ mÅ), while the C9–H bond contracts more ($\Delta r_{C9H} = 5$ mÅ), resulting in a blue shift of its $\nu_{\rm CH}$ mode back to the other $\nu_{\rm CH}$ bands ($\nu_{\rm CH}$ = 2915 vs. 2848 cm⁻¹). The C=N double bond in AmaH⁺(III) is slightly shorter than in AmaH⁺(II) ($r_{CN} = 1.295 \text{ vs. } 1.297 \text{ Å}$), resulting in a small blue shift of the coupled $\beta_{\rm NH_2}$ and $\nu_{\rm CN}$ modes by 8 and 6 cm⁻¹, respectively. The N-H bonds remain at r_{NH} = 1.012 Å with nearly unshifted $\nu_{\text{NH}}^{\text{s/a}}$ modes at 3329/3433 cm⁻¹. Similar to AmaH⁺(II) $(q_{CNH_2} = 0.748 e)$, most of the positive charge is located at the CNH₂⁺ group ($q_{\text{CNH}_2} = 0.755 e$), and the HOMO is localized over the adamantyl framework (Fig. S5, ESI†).

The AmaH⁺(IV) iminium isomer (1 A', C_{s} , $E_{0} = 29.5 \text{ kJ mol}^{-1}$) has a similar structure (both differ only in conformation) as the slightly more stable AmaH⁺(III) minimum and may formally be obtained by addition of an H radical to a radical site of Ama+(II) or Ama⁺(III). However, it is also possible that AmaH⁺(IV) is formed by C3-protonation of Ama accompanied by cage opening.

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The protonation energy for C3-protonation of Ama (927 kJ mol⁻¹) followed by cage opening is only slightly lower than the proton affinity for N-protonation of Ama (PA = 957 kJ mol^{-1}). The AmaH+(IV) structure differs from III mainly by a more closed cage ($\theta_{C1C9C3} = 73.1^{\circ} \text{ vs. } 124.6^{\circ}, r_{C1\cdots C3} = 3.25 \text{ vs. } 4.69 \text{ Å}$) and a chair configuration of the second cyclohexane ring. Consequently, most of the C-C bonds are stretched compared to AmaH⁺(III) $(r_{C1C4} = 1.486 \text{ vs.} 1.480 \text{ Å}, r_{C8C9} = 1.548 \text{ vs. } 1.537 \text{ Å}, r_{C3C9} = 1.535 \text{ vs.}$ 1.527 Å), while the C-C bond lengths of the first aminocyclohexane ring either decrease or remain the same (r_{C2C7} = 1.547 vs. 1.565 Å, $r_{\rm C7C8}$ = 1.539 vs. 1.556 Å, $r_{\rm C5C6}$ = 1.530 vs. 1.531 Å). The variation in the C-H bond lengths is increased from $\Delta r_{\rm CH} = 7 \text{ mÅ in AmaH}^{+}(III) (1.088-1.095 \text{ Å}) \text{ to } \Delta r_{\rm CH} = 11 \text{ mÅ in}$ AmaH⁺(**IV**) (1.088–1.099 Å), leading to four better resolved single convoluted bands ($\nu_{\text{CH}_{\text{m}}} = 2874, 2916, 2948, 2998 \text{ cm}^{-1}$). In particular, the shortened C3-H bond oriented toward the NH₂ group produces a blue shift in the $\nu_{\rm CH}$, mode by $\Delta\nu_{\rm CH}$, = 94 cm⁻¹ to 2998 cm⁻¹. The C=N double bond is slightly elongated to $r_{\rm CN}$ = 1.296 Å, while the N-H bond lengths remain the same ($r_{\rm NH}$ = 1.012 Å). As a result, the coupled $\beta_{\rm NH_2}$ and $\nu_{\rm CN}$ modes are slightly red-shifted to $\nu_{\rm CN}$ = 1533 cm⁻¹ and $\beta_{\rm NH_2}$ = 1665 cm⁻¹, while the $\nu_{\rm NH_2}$ frequencies remain the same $\left(\nu_{\rm NH_2}^{\rm s}=3329~{\rm cm}^{-1},\right.$ $\nu_{\rm NH_2}^{\rm a} = 3432~{\rm cm}^{-1}$). Again, most of the positive charge is located at the CNH $_2^+$ group ($q_{\rm CNH}_2$ = 0.758 e) and the HOMO is localized over the adamantyl framework (Fig. S5, ESI†).

4.2 AmaH⁺Ar clusters

Inspection of Fig. 1 reveals that the predictions for the three iminium isomers **II-IV** of AmaH⁺ are rather similar, while that of the ammonium ion I is rather different, mainly due to the difference in N-H bonding and resulting IR spectra between the NH₃⁺ and NH₂⁺ groups. Prior to detailed comparison to experiment, we briefly consider the impact of Ar-tagging. The effect of Ar on the structural, vibrational, and energetic properties of all AmaH⁺ isomers is indeed very small, so that the discussion on the AmaH⁺Ar isomers is kept short. Details of the computed AmaH⁺Ar structures, energies, charge distributions, and IR spectra are provided in the ESI† (Fig. S6-S10 and Tables S5, S6). In the most stable AmaH⁺Ar isomers, Ar interacts with both the charged NH2/3 group and the C10H15/16 moiety to maximize induction and dispersion forces, with low binding energies of $D_0 = 10.2$, 9.8, 6.9, and 8.9 kJ mol⁻¹ for I-IV, respectively. Significantly, the minor differences in the Ar binding energy are too small to affect the energetic order of the monomer ions. The main impact of the weak interaction with Ar is a reduction in symmetry, resulting in a small splitting of the degenerate NH stretching and bending modes of AmaH⁺(I). The IR spectra calculated for all AmaH⁺Ar isomers for each monomer (I-IV) show only minimal shifts of less than 11 (I), 4 (II), 7 (III), and 8 cm⁻¹ (**IV**) in $\nu_{\text{NH}_{2/3}}$, $\beta_{\text{NH}_{2/3}}$, γ_{NH_3} , and ν_{CN} upon Ar-tagging, respectively. Similar to Ama⁺Ar, ^{47,48} the Ar ligands form in the most stable AmaH⁺Ar isomers weak and strongly nonlinear NH···Ar H-bonds ($R_{NH···Ar} = 2.58-2.86 \text{ Å}, \phi_{ArHN} = 119.8-$ 165.4°), accompanied by additional van der Waals contacts to adjacent CH_2/CH_3 groups ($R_{CH\cdots Ar} = 2.96-3.15$ Å), yielding $D_0 = 8.7-10.3 \text{ kJ mol}^{-1}$. As a result, the involved N-H bonds are slightly stretched (by 1 mÅ), while the involved C-H bonds are shortened (by 1 mÅ) and free C-H bonds can be elongated. These structural effects result in minor red and blue shifts in $\nu_{NH_{2/2}}$ (<11 cm⁻¹), ν_{CH_2} (<6 cm⁻¹) and ν_{CH_3} modes $(<13 \text{ cm}^{-1})$. Charge transfer from AmaH $^{+}$ to Ar is rather small (5–9 me). AmaH $^+$ (I)-Ar(I) with the ammonium core ion has the strongest and a nearly linear NH···Ar H-bond ($R_{NH···Ar} = 2.58 \text{ Å}$, ϕ_{ArHN} = 165.4°), with the largest accompanying charge transfer of 9 me. Due to Ar attachment, the two degenerate $v_{NH_2}^a$ (3301 cm⁻¹) and $\beta_{NH_3}^a$ (1611 cm⁻¹) modes of AmaH⁺(I) split into two separate modes in AmaH⁺(I)-Ar(I), $\nu_{NH_3}^a = 3289/3303 \text{ cm}^{-1}$ and $\beta_{NH_3}^a=1611/1613~cm^{-1}$. In AmaH⁺(II)-Ar(I), Ar binds to the NH₂⁺ and C9H groups, resulting in a blue shift of the corresponding $\nu_{\rm CH}$ mode from 2847 to 2860 cm⁻¹. In the less stable I-Ar(II-V), II-Ar(II-VI), III-Ar(II-VI), and IV-Ar(II-VI) clusters, Ar binds only to the $C_{10}H_{15/16}$ cage, with lower binding energies of $D_0 = 2.0$ 6.2 kJ mol⁻¹ and negligible effects on the monomer properties.

4.3 Assignment of IRPD spectrum

The minor effects of Ar-tagging on the geometries, energies, and IR spectra of the AmaH isomers I-IV justify direct comparison of the latter to the measured IRPD spectrum of AmaH⁺Ar for vibrational and isomer assignments (Table S1, ESI†). Inspection of Fig. 1 reveals immediately the presence of both ammonium and iminium isomers of AmaH⁺. As outlined above, the NH stretch and bend ranges are most decisive. While most of the intense features are readily assigned to the most stable ammonium ion I, with clear signatures of the NH₃⁺ group (E, H, Q, R), the strong features I, S, T, and U cannot be explained by this isomer but fit well to the features of the NH₂⁺ group of the iminium isomers **II-IV**. Specifically, peaks **Q** and **R** (3238 and 3317 cm⁻¹) are attributed to the ν_{NH}^{s} , and degenerate $\nu_{\mathrm{NH_3}}^{\mathrm{a}}$ NH stretch modes predicted at 3214 and 3301 cm⁻¹ of I, respectively, while bands E and H (1453 and 1611 cm⁻¹) arise from the γ_{NH_3} umbrella (1441 cm⁻¹) and degenerate β_{NH_3} bending modes (1611 cm⁻¹), with maximum, mean, and median deviations of 24, 13, and 14 cm⁻¹, respectively, consistent with the widths of the bands (12-21 cm⁻¹) and the small effect of Ar-tagging (≤ 5 cm⁻¹). Actually, bands **H** and R assigned to the doubly degenerate modes are broader than bands E and Q attributed to single transitions, which can readily be explained by splittings of the degenerate modes upon Ar-tagging into two unresolved components with roughly equal intensity. While the predicted splitting for $\beta_{\mathrm{NH_3}}$ is rather small (2 cm $^{-1}$), that for $\nu_{\rm NH_3}^{\rm a}$ is larger (13 cm $^{-1}$) and indeed partly resolved for band **R** (10 cm⁻¹).

Unfortunately, the properties of the NH₂⁺ groups and resulting IR spectra of the iminium ions II-IV are very similar, with differences of $\leq 2/3$ and ≤ 5 cm⁻¹ for $\nu_{NH_2}^{s/a}$ and β_{NH_2} , respectively. Hence, we cannot distinguish between them at the current spectral resolution and consider for the assignment given here the by far most stable of them (II). Following this scenario, bands **S** and **U** (3344 and 3451 cm⁻¹) are assigned to $\nu_{NH_2}^{s}$ (3331 cm⁻¹) **PCCP** Paper

and $\nu_{\text{NH}_2}^{\text{a}}$ (3435 cm⁻¹) of **II**, with deviations of 13 and 16 cm⁻¹, respectively. Peak I (1714 cm⁻¹) is then attributed to β_{NH_2} (1664 cm⁻¹) of **II** which couples strongly with ν_{CN} . The somewhat larger deviation of 50 cm⁻¹ between experiment and calculation is probably due to the different anharmonicity of the $\nu_{\rm CN}$ mode, leading to an improper description of the coupling (including a nonoptimal scaling factor).⁴⁷ Due to its low intensity, $\nu_{\rm CN}$ of **II** is not observed. Band T (3428 cm⁻¹) occurs also in the NH stretch range of the NH₂ group and may be attributed to a $\nu_{NH_2}^a$ mode of, for example, III or IV. This option implies that the large splitting between T and U of 23 cm⁻¹ is not reproduced by the calculations for II-IV. An assignment of T and U to different Ar binding sites of II appears also unlikely, because the predicted shifts upon tagging are less than 4 cm⁻¹. A third alternative is an assignment of T to the $2\beta_{\rm NH_2}$ overtone, which gains intensity via a classical Fermi resonance with $\nu_{\rm NH_2}$. Such intense $2\beta_{\rm NH_2}$ overtones are also observed in the IRPD spectra of $Ama^{+}L_{n}$ clusters, and indeed the position of band T is twice the frequency of band I (1714 cm⁻¹), making this interpretation a likely and currently favored scenario.

The assignments of the NH stretch and bend ranges reveal the presence of both ammonium and iminium ions. Their population ratio can roughly be estimated from the observed integrated peak intensities, the computed IR cross sections, and the reasonable assumptions of similar Ar-tagging and photodissociation efficiencies. When considering the isolated peaks H and I, or peaks Q and U, population ratios of 4:1 and 3:1 are obtained for I and II(-IV), i.e., the AmaH⁺ population and AmaH⁺Ar spectrum is strongly dominated by the ammonium isomer obtained by simple protonation of Ama at the NH₂ group.

With this derived population ratio, we consider now the other spectral ranges, for which clear-cut isomer assignments are less obvious due to similar frequencies and/or spectral congestion. Bands B-D (1209, 1322, 1377 cm⁻¹) are consistent with $\tau_{\rm CH_2}$ and $\gamma_{\rm CH_2}$ modes of the dominant isomer I with respect to both frequency (1206, 1294, 1359 cm⁻¹) and relative intensity. Similarly, peaks F and G (1474 and 1483 cm⁻¹) can be attributed to $\beta_{\text{CH}_{w}}$ modes of I (1469 cm⁻¹), with its strongest IR active modes at 1463 and 1472 cm⁻¹ (26 and 39 km mol⁻¹). The transitions predicted for the minor isomer II in this spectral range mostly overlap (Table S1, ESI†), and the only isomerspecific transition appears to be band A (1187 cm⁻¹), which has no predicted mode of I but fits to $\tau_{\rm CH_2}$ of II (1203 cm⁻¹).

In the CH stretch range, isomer-specific assignments are not as straightforward due to the similar frequencies of $\nu_{\rm CH_n}$ of I and II, but bands K (2872 cm⁻¹) and M (2949 cm⁻¹) may be assigned to I ($\nu_{\rm CH_n}$ = 2899 and 2956 cm⁻¹) and bands J (2853 cm⁻¹), L (2921 cm⁻¹), and N (2973 cm⁻¹) to II ($\nu_{\rm CH}$ = 2848, 2917, and 2977 cm⁻¹) with maximum, mean, and median deviations of 27, 9, and 5 cm⁻¹. In particular, peak J (2853 cm⁻¹) agrees well with the blue-shifted $\nu_{\rm CH}$ mode of II (2847 cm⁻¹), which is another argument for observing II, because none of the other isomers have modes predicted in this frequency range.

The weak bands O and P (3164 and 3185 cm⁻¹) cannot readily be explained by fundamentals of I-IV and thus are likely overtones and combination bands of $\beta_{\rm NH_2}$ and/or $\nu_{\rm CN}$. Similar bands have been observed previously for Ama⁺Ar (3151 cm⁻¹) and AnH⁺Ar (3175 cm⁻¹).^{47,67} In analogy to assigning T as overtone of H of isomer II, O and P are attributed to overtones of the two components of **H** (1611 cm⁻¹). In this scenario, the splitting of the degenerate fundamental upon Ar-tagging is better resolved for the overtone. The corresponding expected overtone of E falls in the rich $\nu_{\rm CH}$ range (2906 cm⁻¹) and is not easily identified.

4.4 Potential energy diagram and production routes

The analysis of the IRPD spectrum of AmaH⁺Ar by B3LYP-D3 calculations reveals the unambiguous spectroscopic fingerprints of (at least) two different AmaH⁺ isomers in the supersonic plasma expansion: the dominant ammonium isomer (I) and the minor iminium isomer (II). The similar iminium ions III and IV cannot be completely ruled out because they have similar predicted IR spectra as II. However, due to their higher relative energy ($E_0 \ge 27 \text{ kJ mol}^{-1}$), their formation is considered unlikely (although kinetic trapping may lead to their significant population). Assuming that only I and II are observed, their population ratio is derived in the range 3:1 to

In an effort to rationalize possible production routes for I and II, we consider the potential energy diagram for Ama, and the various Ama⁺ and AmaH⁺ isomers in Fig. 3. The ionization process of Ama and the formation of the three isomers I-III of Ama+ by vertical ionization and structural rearrangement reactions (cage opening and 1,2, H-shift) have been discussed in detail previously (Fig. S3, ESI†).47 In a bare Ar expansion of Ama, the population ratio of I-III was determined as 10:3:7, although this may change somewhat in a H₂/Ar/He plasma employed here. Starting from Ama, two main reaction pathways are possible. The first route involves N-protonation of Ama most likely by exothermic proton transfer from H₃⁺ (eqn (3)). The second route involves EI/CI of Ama, and subsequent H-addition to isomers I-III of Ama+, most likely by Habstraction from H2 (eqn (5) and (6)), although internal energy resulting from EI/CI is required to overcome the endothermicity of this reaction. The ammonium ion I of AmaH⁺ can be produced by either route, namely N-protonation of Ama or H2 reacting with Ama⁺(I). On the other hand, the iminium ions II–IV of AmaH⁺ are most likely formed via the second route, involving EI/CI of Ama and H₂ reacting with Ama⁺(II,III). However, C-protonation of Ama followed by cage opening, which would lead to AmaH⁺(**IV**), cannot be completely ruled out, because of the comparable protonation energy of 927 kJ mol⁻¹. Moreover, protonation of Ama with H₃⁺ leading to AmaH+(I) is highly exothermic and thus may also produce II-IV by cage opening.

In AmaH⁺(I), N-protonation at the N lone pair elongates the C-N bond and contracts the adjacent C1-C3 bonds, thereby preventing cage opening with an intact NH₃⁺ group. The calculated proton affinity for N-protonation is in good agreement with experiment (PA = 957 vs. 949 kJ mol⁻¹).⁷⁸ Starting from the AmaH+(I) global minimum, a 1,2 H-shift from the NH₃⁺ group to the C3H₂ group can occur, which opens the cage and forms AmaH⁺(IV) at $E_0 = 29.5$ kJ mol⁻¹. However, the

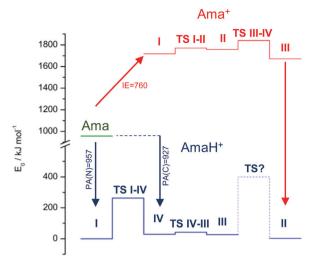


Fig. 3 Potential energy surfaces (minima and transition states) of AmaH⁺ (blue), Ama⁺ (red), and Ama (green) for the protonation and ionization pathways including cage-opening processes. Ionization energy (IE) and proton affinity (PA) values are given in kJ mol⁻¹.

energy barrier for this rearrangement process at $TS(\mathbf{I-IV})$ is rather high ($V_b = 263 \text{ kJ mol}^{-1}$), making this process unlikely. Nonetheless, from $AmaH^+(\mathbf{IV})$ the cage can open further via $TS(\mathbf{IV-III})$ at a very low barrier ($V_b = 14 \text{ kJ mol}^{-1}$) to form $AmaH^+(\mathbf{III})$ at $E_0 = 27.4 \text{ kJ mol}^{-1}$ (\mathbf{III} and \mathbf{IV} differ only in their conformation). This rearrangement is accompanied by a chair to boat conversion of the cyclohexane ring. A rearrangement from $AmaH^+(\mathbf{III})$ to $AmaH^+(\mathbf{II})$ is rather improbable, since this process would require most of the structure ($C_6H_8NH_2$) to flip once around the C8-C10 axis, which probably involves a high barrier. Because of this substantial rearrangement, the associated barrier for $TS(\mathbf{III-II})$ could not be calculated. Hence, we assume that the detected $AmaH^+(\mathbf{II})$ isomer cannot be formed via the protonation pathway and therefore must be formed via the ionization route.

Unlike N-protonation of Ama, ionization leads to a contraction of the C-N bond and a drastic elongation of the C1-C3 bond in $\text{Ama}^+(\mathbf{I})$ ($E_0 = 45.9 \text{ kJ mol}^{-1}$) due to the removal of an electron from the N lone pair and the increased delocalization of this orbital into the adamantyl cage. The computed adiabatic ionization energy of 7.9 eV agrees well with the estimated vertical value (8.6 eV), 53 and both are well below the available maximum electron energy of the EI process (220 eV). As a result, part of the nascent Ama⁺(I) population may overcome the energy barrier at TS(I-II) (V_b = 54.1 kJ mol⁻¹, $E_0 = 100.0 \text{ kJ mol}^{-1}$) for opening the cage. This process generates the bicylic distonic Ama⁺(II) iminium ion (E_0 = 87.4 kJ mol⁻¹) with a primary CH₂• radical center. A much more stable tertiary CR₃ radical center is then formed in the most stable distonic bicyclic iminium ion Ama⁺(III) $(E_0 = 0)$ by 1,2 H-shift from C9H to CH_2^{\bullet} via Ama⁺(TS(II-III)) ($V_b = 81.6 \text{ kJ mol}^{-1}$). This tertiary CR3 radical center is the very attractive for H-atom attachment leading to the formation of AmaH⁺(II). As Ama⁺(III) has already been detected in high abundance in the Ar plasma expansion of Ama,⁴⁷ this formation mechanism of the low-energy AmaH⁺(II) isomer ($E_0 = 3.0 \text{ kJ mol}^{-1}$) is highly plausible.

6. Concluding remarks

In conclusion, we characterize herein the structural, vibrational, and energetic properties of AmaH⁺ ions by Ar-tagging IRPD spectroscopy and dispersion-corrected B3LYP-D3 calculations. To this end, the AmaH⁺ ions are generated in a supersonic plasma expansion generated by electron/chemical ionization of a molecular beam containing Ama, He, and Ar. Significantly, the obtained IRPD spectrum of AmaH⁺Ar provides the first spectroscopic characterization of the structure of this pharmaceutically active ion. The influence of Ar is shown to be negligible by B3LYP-D3 calculations and the evolution of IRPD spectra recorded for AmaH⁺Ar_n with n = 1-3. The IRPD spectra cover the structure-sensitive NH stretch and bend ranges, which reveal the presence of two types of isomers. The dominant population corresponds to N-protonated AmaH+, which is the global minimum on the computed potential energy surface (isomer I, $E_0 = 0$) and the relevant structure for pharmaceutical applications in solution. In addition to this ammonium ion, a smaller population is assigned to the only slightly less stable bicyclic iminium ion (isomer II, $E_0 = 3$ kJ mol⁻¹), which is probably produced by ionization of Ama, followed by opening of the adamantyl cage and subsequent addition of H. A study on AmaH $^{+}$ (H₂O)_n clusters using similar experimental and computational techniques is underway to characterize the impact of microhydration on the structure and reactivity of this fundamental biomolecular ion.

Conflicts of interest

There are no conflicts of interest to declare.

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