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Photoionization cross section of the NH_2 free radical in the 11.1-15.7 eV energy range

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Abstract

The NH_2 radical is a key component in many astrophysical environments, both in its neutral and cationic forms, being involved in the formation of complex N-bearing species. To gain insight into the photochemical processes into which it operates and to model accurately the ensuing chemical networks, the knowledge of its photoionization efficiency is required, but no quantitative determination has been carried out so far. Combining a flow-tube H-abstraction radical source, a double imaging photoelectron-photoion spectrometer and a vacuum-ultraviolet synchrotron excitation, the absolute photoionization cross section of the amino radical has been measured in the present

work for the first time at two photon energies: $\sigma_{\text{ion}}^{\text{NH}_2}(12.7 \text{ eV}) = 7.8 \pm 2.2 \text{ Mb}$ and $\sigma_{\text{ion}}^{\text{NH}_2}(13.2 \text{ eV}) = 7.8 \pm 2.0 \text{ Mb}$. These values have been employed to scale the total ion yield previously recorded by Gibson *et al.* (*JCP*, **83**, pp 4319-4328 (1985)). The resulting cross section curve spanning the 11.1-15.7 eV energy range will help in refining the current astrophysical models.

Introduction

The amino or amidogen radical (NH_2) is a molecule of great astrophysical interest. In a similar way to ammonia, it constitutes a building block from which more complex N-bearing species can derive (formamide NH_2CHO , urea H_2NCONH_2 , polycyclic nitrogen-containing hydrocarbons, amino acids, proteins, *etc.*).^{1,2} Additional reactivity can be expected from neutral NH_2 , an open shell species, and even more from the NH_2^+ cation which is a double radical isoelectronic to the methylene radical CH_2 . NH_2 is present in many astrophysical media in the gas phase,³⁻⁵ and within or in the close vicinity of solids (grains and ices),^{6,7} in particular comets, and is implicated in chemical reactions therein.^{7,8} Sandford *et al.*⁶ reported, using laboratory experiments, the formation of pyrimidine ($\text{C}_4\text{H}_4\text{N}_2$) in ices containing H_2O , NH_3 , CH_3OH , and CH_4 following UV photolysis. They went on to expose the major role that neutral NH_2 then plays in reacting with pyrimidine to form cytosine, a nucleobase. In addition, NH_2 is one of the major fragments formed in the ultraviolet/vacuum-ultraviolet photodissociation of NH_3 , an important constituent of many astrophysical environments, including comets such as Churyumov-Gerasimenko.⁹

In terms of spectroscopy, neutral NH_2 has been widely studied since its first observation in 1952 by Herzberg *et al.*,¹⁰ from pure rotational^{11,12} to electronic studies.¹³⁻¹⁵ There are fewer works however at higher energies, around the ionization potential (IP) and on the NH_2^+ cation itself. In 1980, Dunlavey *et al.*¹⁶ performed the first photoelectron study on NH_2 , employing a He lamp and an amidogen source based on the H-abstraction reaction: $\text{NH}_3 + \text{F} \rightarrow \text{NH}_2 + \text{HF}$. They located the three lowest electronic states of the cation ($\tilde{X}^+ \text{ } ^3\text{B}_1$,

$\tilde{a}^+ \ ^1a_1$ and $\tilde{b}^+ \ ^1B_1$) and described their vibrational structure. High-lying bending modes of the two lowest electronic states of NH_2^+ were more recently investigated by Holzmeier *et al.*¹⁷ *via* threshold-photoelectron spectroscopy, using an almost identical setup to that employed in the present work. The triplet-singlet splitting between these states was studied in more detail using pulsed-field-ionization zero-kinetic-energy spectroscopy.^{18,19} These high resolution studies yielded a full rotational description of the two lowest electronic states of the cation, and the most precise determination to date of the ionization energy $IE(\text{NH}_2) = 90083.8(10) \text{ cm}^{-1}$ ($= 11.1689(1) \text{ eV}$). The photoionization of NH_2 has also been studied by accurate calculations.^{20,21}

To our knowledge, no experimental determination of the absolute photoionization cross section of NH_2 has been published until now. Only its ion yield from threshold up to 16.6 eV has been measured by Gibson *et al.*²² In their study, NH_2 was produced by H-addition onto N_2H_4 which initiated a set of reactions finally producing NH_2 . Their paper provides a detailed discussion on the thermochemistry of the NH_x compounds (N-H bond energies and formation enthalpies) and a first determination of appearance energy of the NH_2 dissociative ionization channel leading to NH^+ (17.19 eV). A spectroscopic interpretation of the features present in the NH_2^+ ion yield is also given.

In the present paper, we report the first experimental measurement of the NH_2 absolute photoionization cross section in the 11.1-15.7 eV energy range.

Experimental section

The experiments were carried out on the DESIRS beamline²³ of the French synchrotron facility SOLEIL. The details of the experiment have been published previously,²⁴ and include the specificities of this setup and the procedure for determining the radical cross section, as well as detailed descriptions of energy calibrations and energy resolution.^{25,26} Briefly, F atoms cre-

ated from the dissociation of F_2 in a microwave discharge go on to react with helium-diluted NH_3 in a flow-tube reactor. Experimental conditions are controlled *via* mass spectrometry to optimize the single-H abstraction of NH_3 and to minimize all other side reactions (F addition, double-H abstraction, radical-radical reactions, *etc.*). After passing through two skimmers, the products from the reactor perpendicularly cross the monochromatized synchrotron radiation beam within the DELICIOUS III double imaging photoelectron/photoion spectrometer.²⁷ The resulting ionization produces ions and electrons which are simultaneously collected using a 177 V/cm extraction field, which ensures a 100% particle collection efficiency at the photon energies studied here. When recording ionization yield, the photon resolution was set to $\delta E = 4$ meV over the whole scan range. For the absolute measurements, it was increased to $\delta E = 10$ meV. This difference in photon energy resolution is not however important as the fixed energy measurements were purposefully carried out in spectral regions off-resonance with any structures, thus independent of the resolution. The beamline was equipped with a gas filter containing Ar which removed any high harmonics stemming from the undulator in the final monochromatized radiation. Resulting Ar absorption lines present in the ion yield allowed the calibration of the photon energy to an accuracy of around 4 meV. The ion yield was recorded using 4 meV energy steps in two different measurements: one from 10.8 eV up to 14.3 eV and one from 13.4 eV up to 15.5 eV. The large overlap between the two scans enabled an unambiguous intensity scaling of the two measurements. A photodiode (AXUV, IRD) was used to correct the spectra from the incident VUV flux.

Results and discussion

The ion yield from this work is compared to that of Gibson *et al.*²² in Fig. 1. The similarities between the two spectra are clear up to 13.6 eV and validate the measurements performed in the present work within this spectral range. Both spectra rise characteristically slowly from the first ionization potential at ~ 11.17 eV¹⁹ to around 12.5 eV, *i.e.* the first excited

Figure 1: a) Ion yield recorded in the present work for $m/q = 16$ a.m.u. and attributed mainly to the NH_2^+ cation. The off-scale sharp resonances at 14.1 eV correspond to the atomic oxygen autoionization resonances. Purple asterisks mark Ar absorption lines from the beamline gas filter; b) NH_2^+ ion yield measured by Gibson *et al.*²² The blue dashed lines locate the three lowest electronic states of NH_2^+ .¹⁶

state ($\tilde{a}^+ {}^1A_1$) of NH_2^+ . During this increase, resonances punctuate the spectrum, which can be attributed to autoionizing Rydberg states converging to the $\tilde{a}^+ {}^1A_1$ state.¹⁶ Above 12.5 eV, the ion yield is practically flat, but rises slightly at higher energies. In our spectrum, dominant resonances from atomic oxygen are present at around 14.1 eV. This observation shows that an O^+ signal issuing from H_2O (see below) contaminates the NH_2^+ ion signal in our experiments, both cations being recorded in the same $m/q = 16$ a.m.u. mass channel. This contamination must therefore be addressed and is discussed below. Note that the ion yield of Gibson *et al.* does not contain any O^+ contamination. In their experiment, their radicals were produced using $\text{H} + \text{N}_2\text{H}_4$ reaction. Their NH_2^+ signal contains a contribution issuing from dissociative ionization of N_2H_4 and NH_3 (side-product) above 15.7 eV. They nevertheless succeeded in correcting the NH_2^+ signal from the former process. Thus their ion yield corresponds to ionization of neutral NH_2 from the *IP* up to 15.7 eV.

Figure 2: Panels a) to c): mass spectra recorded at 12.7 eV with NH_3 in the source and the microwave discharge turned off (panel a)), on (panel b)), and resulting difference spectrum (panel c)). Panels d) to f): same as panels a) to c) but for a photon energy of 14.0 eV. Panels g) to i): same as panels a) to c) but for a photon energy of 17.5 eV and without NH_3 injected at the source. In each column, the signal has been normalized to the most intense peak of the upper panel. See text for details.

Typical mass spectra are displayed in Fig. 2. Panels a) to c) and panels d) to f) correspond to spectra recorded at 12.7 and 14.0 eV, respectively, and normalized to the NH_3^+ signal obtained with the microwave discharge switched off. With the discharge turned on, the conditions were optimized to favour the production of NH_2 from NH_3 precursor whilst minimizing parasitic reactions. In particular, the absence of NH^+ at $m/q = 15$ a.m.u. in the 14.0 eV spectra (panels e) and f)) (*i.e.* above $IE(\text{NH})=13.480$ eV²⁴) shows that NH is not produced in the reactor *via* double-H abstraction.²⁵ As seen in panels a) to f) of Fig. 2, water is present as an impurity in the experiment, and it is almost completely consumed when the F-atom-producing discharge is turned on (panels b) and e)). It could lead to the formation of OH *via* the parasitic reaction $\text{H}_2\text{O} + \text{F} \rightarrow \text{OH} + \text{HF}$ which could then contaminate the NH_3^+ signal at $m/q = 17$ a.m.u. rendering the exploitation of the mass spectra difficult if not impossible. For this reason, additional mass spectra were recorded, within the same conditions but without any NH_3 , at a photon energy of 17.5 eV to be above the *IP* of any potentially produced fragments, including HF ($IE(\text{HF}) = 16.03$ eV²⁸) the by-product of H abstractions by F. They are displayed in the right-hand panels of Fig. 2 (panels g) to i)). Note that in this case the mass signals have been normalized to that of H_2O^+ recorded without discharge (panel g)). This explains the amplified appearance of the water peak although the abundance of neutral water is the same as in the two left columns. Since the photoionization cross section of water at 17.5 eV is about twice as large as at 14.0 eV, see ref. 29, the normalized signals observed in panels g) and h), in particular at $m/q = 16$ a.m.u., are actually very weak compared to those of panels d) and e)). These ammonia-free spectra show that water is consumed by switching the discharge on (panels h) and i)), pointing towards a contamination upstream from the microwave discharge on the F_2 gas line. The difference spectrum of panel i) illustrates the consumption of H_2O and production of O and HF ($\text{H}_2\text{O} + 2\text{F} \rightarrow \text{O} + 2\text{HF}$). In the presence of NH_3 , atomic fluorine reacts mainly with NH_3 giving $\text{HF} + \text{NH}_2$ ($k = 10^{-10}$ cm³.s⁻¹ at 298 K, see Ref. 30). As the reaction rates of $\text{OH} + \text{NH}_3$ and $\text{OH} + \text{NH}_2$ are low at room temperature ($k = 1.6 \cdot 10^{-13}$ cm³.s⁻¹ and $\sim 10^{-12}$ cm³.s⁻¹,

respectively),³¹ OH will mainly react either with atomic fluorine to give $O + HF$ or on the walls, but it will not react with NH_3 or NH_2 . Moreover, very little OH radical is left by the time the molecules enter the spectrometer and are ionized by the synchrotron radiation, likely because they are produced close to the discharge and undergo self-reactions (producing O and H_2O), reaction with O atoms (yielding O_2) or reactions on the walls. The presence of OH in the experiment can only be detected at energies above the IP (13.0170 eV),³² hence it would have no consequences in the absolute values at 12.7 eV. In the present work, no OH is detected even above 13.0170 eV as shown by the identical curves in Fig. 1. Oxygen atoms self-react producing O_2 and there also seems to be some reactivity with N_2 impurity producing NO (both products identified *via* the recording of their ion yield).²⁵ The absence of $m/q = 17$ a.m.u. in the spectra of panels h) and i) of Fig. 2 further demonstrates that there is no contamination of the NH_3^+ signal by that of OH^+ in the experiment. The presence of O atoms in the experiment is however confirmed, which will induce a contamination of the NH_2^+ signal at $m/q = 16$ a.m.u. for photon energies above $IE(O) = 13.61$ eV,³³ and will thus require that reliable absolute measurements be performed below 13.61 eV.

Absolute measurements of the NH_2 photoionization cross section were thus undertaken at two energies, 12.7 and 13.2 eV located on a plateau (see Fig. 1), to probe the NH_2 cross section over a greater range, thus improving the precision. The procedure is the same as used in a previous work on the OH radical.^{25,34,35} The difference between mass spectra recorded with the discharge on and mass spectra with the discharge off is a depletion of $m/q = 17$ a.m.u. signal in favor of $m/q = 16$ a.m.u.. This change is the result of the consumption of NH_3 by F atoms producing NH_2 . Applying matter conservation to the number densities, we have $\Delta(n_{NH_3}) = n_{NH_3}^{off} - n_{NH_3}^{on} = n_{NH_2}^{on}$. As NH_2^+ and NH_3^+ are neighboring masses, we assume that their transmission and detection efficiencies are the same. We also neglect any wall loss of NH_2 . In order to verify this, we measured the ratio of produced NH_2 with respect to the quantity of consumed NH_3 whilst varying the injector distance. We found this ratio to be

independent of the injector distance which confirms that NH_2 is not lost to the walls within our reaction times. The proportionality law between ion signal, number of irradiated species and photoionization cross sections thus leads to:

$$\sigma_{\text{NH}_2}^{\text{ion}} = \sigma_{\text{NH}_3}^{\text{ion}} \times \frac{S_{\text{NH}_2^+}}{\Delta(S_{\text{NH}_3^+})} \quad (1)$$

In Eq.(1), $\Delta(S_{\text{NH}_3^+})$ and $S_{\text{NH}_2^+}$ are measured experimentally from the mass spectra. The NH_3 photoionization cross section is well known.^{36,37} We used the values of Samson *et al.*³⁶ of 8.88 ± 0.27 and 8.20 ± 0.25 Mb at 12.7 and 13.2 eV, respectively, and considered the stated accuracy on these values of 3% as being 2σ accuracy. The NH_2 photoionization cross section uncertainty was then derived *via* a Monte Carlo uncertainty propagation procedure applied on Eq.(1). We found: $\sigma_{\text{ion}}^{\text{NH}_2}(12.7 \text{ eV}) = 7.8 \pm 2.2$ Mb and $\sigma_{\text{ion}}^{\text{NH}_2}(13.2 \text{ eV}) = 7.8 \pm 2.0$ Mb.

These absolute measurements were further used to set the NH_2^+ ion yield of Gibson *et al.*²² to an absolute scale up to 15.7 eV. The resulting curve is displayed in Fig. 3. Error bars were evaluated by taking the relative uncertainty at each of the two fixed energy measurements and propagating them over the whole scan range. The given final uncertainty, represented as light blue error bars in Fig. 3, is the minimum relative uncertainty of the two. A third absolute measurement performed at 14 eV is reported on this curve without any attempt to correct it from the expected oxygen contamination: $\sigma_{\text{ion}}^{m/q=16}(14.0 \text{ eV}) = 8.1 \pm 3.2$ Mb. It constitutes an upper estimate of the NH_2 cross section (Eq.(1)). The corresponding value lies within the estimated error bars and is still in excellent agreement with the scaled ion yield, indicating that the O^+ contribution has a negligible impact on the cross section determination. Nevertheless note that this point was not employed in the absolute scaling procedure.

Figure 3: The NH_2^+ ion yield of Gibson *et al.*²² scaled to an absolute photoionization cross section from threshold up to 15.7 eV. The absolute measurements undertaken in this work at 12.7, 13.2 and 14.0 eV are depicted as red and orange crosses along with their associated 2σ error bars. The light blue area represents 2σ error bars carried over the whole study range. The green curve recalls the cross section used in the Leiden astrophysical database.³⁸

Concluding remarks

The newly measured cross section values of this work can be compared to those available in databases dedicated to astrophysical models. For instance the Leiden database³⁸ proposes NH_2 photoionization cross section values using the ion yield of Gibson *et al.*²² that is arbitrarily set to 20 Mb at 15.5 eV to be in line with other molecules of their database. As shown in Fig. 3 where the resulting curve is displayed in green, this scaling factor overestimates cross section values by about a factor 2 and thus leads to an overestimation of the NH_2 photoionization process in models relying on this database. The correction of this overestimation might lead to a greater predicted abundance of neutral NH_2 in different regions testifying to an increased importance of NH_2 as a reactive intermediate in photodissociation regions as well as protoplanetary and protostellar envelopes where UV radiation and cosmic ray ionization is plentiful.³⁹ The present work illustrates the importance of an accurate determination of VUV photoionization cross sections of astrophysical species, especially of free radicals, in order to refine photochemical models.

Our measured values will be particularly useful in any laboratory experiments using mass-spectrometry coupled with single-photon ionization to derive quantitative data (e.g. branching ratio measurements of photodissociation channels following the experimental scheme of Ref. 40).

Finally, this first experimental measurement of the NH_2 photoionization cross section opens new possibilities for deriving that of the NH radical, which has also been detected in comets,⁴¹ in the sun,⁴² or in the interstellar media.⁴³ The NH cross-section has yet to be reported, but is achievable with this setup by tuning the flow-tube conditions to allow both a single- and a double-H abstractions. This operation mode is more challenging, but will be attempted in a future experimental campaign.

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Supporting Information Available

See supplementary material for the photoionization cross section data of NH_2 as a function of photon energy from 11.1 to 15.7 eV.

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Graphical TOC Entry