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An angle-resolved dissociative photoionization study of the c4Σ− state in O2+ using the TPEPICO technique

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Abstract

We have investigated the angular distributions of O+(4S) ions produced from dissociative photoionization of O2+ c4Σ− (ν = 0, 1) using the TPEPICO technique, i.e. by measuring the coincidence yield between threshold photoelectrons and photoions. The vibrational levels have distinctly different lifetimes, τν, which diminish their inherent anisotropic photoion angular distribution characterized by a β parameter. We obtain τ1 = 6.0 ± 0.3 × 10−14 s and a lower limit on τ0 of ≈1 × 10−12 s, in broad agreement with other experimental studies using different methods, and find that β = 0.40 ± 0.05, which is significantly at variance with the predicted value of ≥1.6.

1. Introduction

Inner valence photoionization of molecules can result in dissociative photoionization (DPI) into a variety of final states, and studies of both spectroscopy and fragmentation dynamics in this energy region continue to be theoretically and experimentally challenging, even for diatomic molecules. DPI is of great interest as, in the case of O2 for example, it is a source of energetic ions and neutral species that contribute to the oxygen chemistry of the Earth’s upper atmosphere [e.g. 1–3]. Moreover, O+ ions, thought to be produced by DPI of O2, have been recently observed in the tenuous atmosphere associated with Saturn’s icy A ring system [4, 5]. This process together with dissociative ionization via charged particle collisions [6, 7] produces O+ ions in other icy planetary regions, such as Jupiter’s moons Europa and Ganymede [6–8]. Consequently, there is a sustained interest in processes that produce energetic oxygen ions and atoms.

In this work we restrict ourselves to the c4Σ− state in O2+ at ~24.56 eV (above the O2 X3Σ− ground state), which has a shallow minimum in its potential well that supports two distinct quasi-bound vibrational levels (ν = 0, 1). This existence of such a strongly predissociative state partly explains why there have been numerous theoretical and experimental studies of the c4Σ− state over the years. As a dissociation product is metastable O(1D) atoms (only 1.97 eV above the ground state O(3P)), this process also has direct relevance to stratospheric photochemistry [1–3].

DPI of O2 between 20 and 28 eV has been recently explored in detail using electron–ion vector correlation methods, examining both the electron–ion kinetic energy correlation [9] and the molecular frame photoelectron angular distributions [10]. That latter study also gave laboratory frame ion angular distributions given by

\[
\frac{d\sigma}{d\Omega} = \frac{\sigma_o}{4\pi} (1 + \beta_o \cdot P_2 (\cos \theta)) = \frac{\sigma_o}{4\pi} \left(1 + \frac{\beta_o}{2} (3 \cos^2 \theta - 1)\right),
\]

where θ is measured with respect to the polarization axis and is characterized by an asymmetry parameter, βo, whose range lies between −1 and +2. In the case of the c4Σ− state, the authors found a major discrepancy between their theoretical predictions and experimental observations. In [10] the authors determine βo, centred at ~1.9 eV (with 1.5 < Eo < 3.2 eV) in coincidence with ~2.7 eV electrons (with 1.2 < E< 4.5 eV) for a photon energy of 27.35 eV. Their measured βo value was ≈0.1 ± 0.05. The effect of rotation, due to the lifetime, on
the theoretical asymmetry parameter, $\beta^T_{\alpha\alpha}$, for a non-rotating molecule is considered in [10] and found that $\beta_{\alpha\alpha}$ should reduce from $\approx 1.4$ [11] to $\approx 0.8$. That study also measured $\beta_{\alpha\alpha}$ to be $\approx 0.3$ and $0.35$ for $\nu = 0$ and 1 levels, respectively, at $\sim 100$ meV above their thresholds. Lafaosse et al [10] recognized the appreciable discrepancy between theory and experiment and suggested that it could be due to either an underestimate in their apparatus function with large extraction fields or a lack of convergence in the calculation with respect to the inclusion of ions states. As this casts doubt on the reliability of the experimental study and, indeed, the technique, it is important to re-examine their findings using a different method.

The vibrational levels of the $c^4 \Sigma^-_u$ state in $\text{O}_2^+$ have distinctly different lifetimes, $\tau_{\nu}$, due to predissociation, which reduces the state’s inherent anisotropic photoion angular distribution for the non-rotating molecule. As will be reviewed below, there has been much discussion in the published literature on the $\tau_{\nu}$ values, and the best experimental value (technically a ‘lower limit’) for $\tau_{0}$ is $\sim 20$ times smaller than current predictions. If one could have confidence in the theoretical asymmetry parameter for the $c^4 \Sigma^-_u$ state, then an analysis of the observed ionic angular distributions would give a direct measure of the lifetime as a function of the vibrational quantum number. Moreover, this approach would have general applicability to other predissociating states in diatomic molecules. The present experimental study therefore seeks to clarify the discrepancy observed by Lafaosse et al [10] and provide further insight on the values of $\tau_{\nu}$. To place this work in context, we briefly outline current pertinent knowledge concerning the $c^4 \Sigma^-_u$ state.

The $\nu = 1$ level dissociates almost exclusively to the $\text{O}^+(4S) + \text{O}^+(2P)$ limit (designated as L2—see table 1) at $20.700$ eV [13–15]. The $\nu = 1$ level’s decay to the L2 limit is due to tunnelling through the potential barrier and hence its lifetime, $\tau_1$, is critically determined by the shape of the potential. Pulse-field ionization photoelectron (PFI-PE) experiments [16] determined $\tau_1$ as $6.9 \pm 0.7 \times 10^{-14}$ s and this has been recently supported by theoretical studies [17, 18].

In contrast, the $\nu = 0$ level lives long enough to fluoresce to the $b^3 \Sigma^-_g$ state [19, 20] and dissociative ionization competes with radiative decay. Two limits have been clearly established in the dissociative ionization channel, namely L1 and L2 (see table 1) with a branching ratio of approximately 1:2 [13, 14, 20, 21]. Akahori et al [14] also find a weak L5 contribution ($\sim 5\%$) after subtracting L5 yield due to the underlying continuum, a background contribution that is also observed by [13, 15, 20]. Richard-Viard et al [20] conclude that decay to (a) the L2 limit occurs via tunnelling and (b) the L1 limit via the spin–orbit coupling to the $^4\Pi_u$ state. They also quantify the $\text{O}^+ / \text{O}_2^+$ ratio as $6 \pm 1$ for the $\nu = 0$ level; i.e. an $\sim 15\%$ fluorescence branching ratio.

An early theoretical study by Tanaka and Yoshimine [23] took the tunnelling lifetime for $\nu = 0$ to be the same as the estimated radiative lifetime, namely $\tau_f \sim 20 \times 10^{-9}$ s, resulting in equal probabilities of fluorescence and DPI for $\nu = 0$, i.e. $\tau_0 \sim 10 \times 10^{-9}$ s. However, using the fluorescence branching ratio, $\tau_f$, of $\sim 15\%$ from [20] and

$$\frac{1}{\tau_0} \geq \frac{1}{\tau_f}$$

reduces $\tau_0$ to $\leq 3 \times 10^{-9}$ s. As is evident, reliable knowledge of the fluorescence lifetime would be extremely valuable, yet this does not appear to have been measured at this time. Tanaka and Yoshimine [23] also provide a number of theoretical calculations, one of which has $\tau$ values for $\nu = 0$, 1 two orders of magnitude smaller than their final values (see table 2). They considered those lifetimes to be too short, given the assumed value of $\tau_f$.

The PFI-PE study of Evans et al [16], mentioned above, determined $\tau_0$ to be $2.7 \pm 0.3 \times 10^{-13}$ s, four orders of magnitude smaller than that from [23]. Although the subsequent theoretical study by Liebel et al [24] generally favoured ‘fast’ dissociation over ‘slow’ dissociation of [23], the $\tau_0$ value from [16] was criticized in the study by Hikosaka et al [18] as being too prompt. From their experimental data they place a lower limit on $\tau_0$ as $6 \times 10^{-13}$ s and introduce a qualitative theoretical model resulting in a $\tau_0$ value of $\sim 1.3 \times 10^{-11}$ s, which they caution should be viewed as a ‘very rough estimate’. Two further theoretical studies [17, 25] now report $\tau_0$ to be $\approx 1.2 \times 10^{-11}$ s. Those studies, however, find $\sim 99\%$ of the dissociative ionization results in L2; this agrees with experiment for $\nu = 1$, but not $\nu = 0$—as mentioned earlier, which has substantial decay to L1. These latter theoretical studies incorporated interactions between overlapping vibrational levels in the continuum, which reduces the slow dissociative ionization lifetimes from [23] by two orders of magnitude. The vibrational spacing of 0.192 eV corresponds to a vibrational period of $2.15 \times 10^{-14}$ s. Using $\tau_0 = 1.2 \times 10^{-11}$ s and $\tau_1 = 6.9 \times 10^{-14}$ s implies that $\text{O}_2^+$ ($c^4 \Sigma^-_u$) in the $\nu = 0$ and 1 levels execute $\sim 560$ and 3 vibrations, respectively, prior to dissociation.

### Table 1. The lowest five dissociative ionization channels in $\text{O}_2^+$ from [21, 22].

<table>
<thead>
<tr>
<th>Label</th>
<th>Products</th>
<th>Dissociation energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>O(4P) + O(4S)</td>
<td>18.733</td>
</tr>
<tr>
<td>L2</td>
<td>O(4D) + O(5S)</td>
<td>20.700</td>
</tr>
<tr>
<td>L3</td>
<td>O(4P) + O(5D)</td>
<td>22.057</td>
</tr>
<tr>
<td>L4</td>
<td>O(3S) + O(5S)</td>
<td>22.923</td>
</tr>
<tr>
<td>L5</td>
<td>O(4P) + O(5P)</td>
<td>23.750</td>
</tr>
</tbody>
</table>

### 2. Experimental details

We have investigated the angular distributions of 2 eV O(4S) ions produced from DPI of $\text{O}_2^+$ $c^4 \Sigma^-_u$ ($\nu = 0, 1$) using the threshold photoelectron–photoion coincidence (TPEPICO) technique. The experiments were performed using a dual toroidal spectrometer [26] in conjunction with linearly polarized synchrotron radiation on the VLS-PM (undulator) beamline at the Canadian Light Source [27]. The apparatus has been previously used for $(\gamma,e)$ studies [e.g. 28] and threshold photoelectron spectroscopy (TPES) [29, 30];
here we use the apparatus for ion–electron coincidences for the first time and so we briefly outline pertinent details.

The spectrometer consists of two toroidal analysers configured to detect charged particles emitted in the plane orthogonal to the incoming photon beam, which is crossed with an effusive gas jet emanating from a hypodermic needle as shown in figure 1. An adaptation of the penetrating-field technique [31] was used to extract efficiently and selectively the charged particle’s emission angle (measured relative to the direction of the extraction optics and these are eliminated by the focusing properties of the electrostatic analyser. The acceptance angles and configuration indicated in figure 1. Figure 1.

<table>
<thead>
<tr>
<th>Theory/experiment</th>
<th>$\nu$ (eV)</th>
<th>$\nu$ (eV)</th>
<th>$\nu$ (eV)</th>
</tr>
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<tr>
<td></td>
<td>$c^i \Sigma^-$</td>
<td>$v = 0$</td>
<td>$v = 1$</td>
</tr>
<tr>
<td>$\hbar \nu$ (eV)</td>
<td>24.564</td>
<td>24.756</td>
<td>25.005</td>
</tr>
<tr>
<td>$\Gamma_0$ (meV)</td>
<td>$2.3 \times 10^{-5}$</td>
<td>$2.0 \times 10^{-9}$</td>
<td>$0.013$</td>
</tr>
<tr>
<td>$\tau_0$ (s)</td>
<td>$20 \times 10^{-9}$</td>
<td>$3.6$</td>
<td>$1.8 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\Gamma_1$ (meV)</td>
<td>$2.4$</td>
<td>$9.5$</td>
<td>$6.9 \times 10^{-14}$</td>
</tr>
<tr>
<td>$\tau_1$ (s)</td>
<td>$2.7(3) \times 10^{-13}$</td>
<td>$10.4$</td>
<td>$6.3 \times 10^{-14}$</td>
</tr>
<tr>
<td>$\Gamma_2$ (meV)</td>
<td>$0.19$</td>
<td>$9.5$</td>
<td>$6.9 \times 10^{-14}$</td>
</tr>
<tr>
<td>$\tau_2$ (s)</td>
<td>$3.4 \times 10^{-12}$</td>
<td>$13.2$</td>
<td>$4.99 \times 10^{-14}$</td>
</tr>
<tr>
<td>This work</td>
<td>$0.056$</td>
<td>$9.7$</td>
<td>$6.8 \times 10^{-14}$</td>
</tr>
<tr>
<td>$\approx 1$</td>
<td>$1.0 \times 10^{-12}$</td>
<td>$14.1 \times 10^{-12}$</td>
<td>$120 \pm 20$</td>
</tr>
</tbody>
</table>

$^{a}$ From [35]. The calculated energies from [25] are 0.108 meV higher and the observed value for $v = 2$ in [15] is 24.96 eV.
$^{b}$ Predissociation lifetimes only, which are the dominant decay mechanism. However, when comparing with experimental values for the $v = 0$ level, one should note that the lifetime is slightly shorter ($\Gamma_0$ wider) than calculated due to the fluorescence channel.
$^{c}$ Single and double excitation configuration interaction (SDCI).
$^{d}$ 1.1 meV is their upper limit from experimental observation, corresponding to a lower limit on $\tau_0$; 0.05 is an estimate from the model presented in [18]. They support [16] in their value for $\tau_1$. The focusing properties of the electrostatic analyser allow the charged particle’s emission angle (measured relative to the light polarization axis) to be mapped onto a two-dimensional resistive anode encoder [26]. The energy-resolved image on the ion detector is arc-shaped with positions around the perimeter corresponding to the emission angle. A coincidence event is when both (ion and electron) detectors register a count within a specified time window, in this case 20 $\mu$s. In the TPEPICO data acquisition mode, ($x,y,\Delta t$) are recorded for each coincidence event, where $\Delta t$ is the time difference between the electron and the ion signal and ($x,y$) are the ion detection coordinates on the position-sensitive detector. Post-processing the $\Delta t$ data as a time histogram shows a peak of ‘true’ coincidences upon a constant background of ‘random’ coincidences. The ‘true’ coincidence peak was $\sim 1.5 \mu$s wide (FWHM) and the true-random ratio was $\sim 7:1$. The corresponding ion ($x,y$) data are converted to the polar coordinates ($r,\theta$) and the size of the angular intervals into which the data are processed is chosen later to correspond with...
20 20.5 21 21.5 22 22.5 23 23.5 24 24.5 25

Figure 2. The threshold photoelectron spectrum for $O_2^+$ between 20 and 25 eV taken with an accumulation time of 4 s per point, in 2 meV steps, and a vacuum chamber pressure of $\sim 3 \times 10^{-6}$ torr. The dissociative ionization limits L2–5 are indicated (see table 1), as are the two most intense vibrational series: $B^2 \Sigma_g^+ \rightarrow c^4 \Sigma_u^-$; the spectroscopy in this region discussed at length in [15, 33–37 and references therein].

the available statistics. In this case, $10^6$ intervals in the angle $\theta_i$ were used for all the presented data. The ‘true’ coincidence angular distribution was obtained by subtracting the ‘random’ angular distribution from that of the total (‘true’ plus ‘random’) coincidence yield using standard procedures (see [26] and references therein). Since the random coincidence ‘window’ was 17.5 $\mu$s wide, seven times wider than the base width of the true ‘window’, this provided good statistical precision when subtracting these counts to obtain the true coincidences. The angular resolution, $\Delta \theta$, is deemed to be smaller than the angular interval based on our experience with $(\gamma,2e)$ studies [28] and, when measuring the He$^+$ ($n=1$) photoelectron angular distribution for 2 eV electrons, we observe the expected characteristic $\beta = 2$ pattern.

Due to axial recoil in a homonuclear diatomic molecule, the ion energy is simply given by

$$E_{O^+} = \frac{1}{2} (h\nu - D),$$  

where the dissociation limit(s), $D$, is given in table 1. As the threshold photoelectron yield peaks at $h\nu = 24.564$ and 24.756 eV for $\nu = 0$ and 1 levels, respectively, the corresponding $E_{O^+}$ values using equation (3) are 1.932 eV and 2.028 eV for the L2 dissociation limit. The toroidal analyser used to detect ions was operated with an energy resolution of $\approx 0.5$ eV, which is much broader than the $\sim 100$ meV spacing when set to detect 2.0 eV ions, and can readily separate ions from the neighbouring L1 and L3 limits.

3. Results and discussion

A survey threshold photoelectron spectrum displaying the states and dissociation limits between 20 and 25 eV is presented in figure 2. This $O_2^+$ spectrum is in excellent agreement with the earlier threshold studies of Guyon and Nenner [32], Ellis et al [15] and Tanaka et al [33]. That latter study had a resolution of $\sim 2$ meV FWHM in the 18–24 eV energy range and also used a supersonic beam to rotationally cool the molecules. The spectroscopy in this energy region has also been recently studied theoretically [34].

A zoomed region of the $c^4 \Sigma_u^-$ state is shown in figure 3. As in other photoelectron studies [15, 31, 34], a very weak broad feature corresponding to $\nu = 2$ is observed at $\approx 24.97$ eV on the sloping background of the $C^2 \Sigma_u^-$ continuum [33]. We estimate its energy width to be $\sim 120 \pm 20$ meV, which is larger than the 40 meV observed in [34] and in remarkable agreement with the predicted values given in table 1.

We can also measure the increase in peak widths of the $\nu = 0$ and $\nu = 1$ vibration levels over the instrumental width determined earlier. The rotational profile [16, 25] shows that the main contribution to the rising edge of the threshold peak...
At 24.756 eV, 2eV O\(^+\) ions can be produced by DPI from both ν = 1 and 0 levels, unlike the lower photon energy which is below the ν = 1 threshold. As mentioned above, the underlying continuum does not decay to L2, but to L5; hence, this does not contribute to the 2 eV ion yield. We take the relative proportion of ν = 1 and 0 levels at the upper photon energy to be given by the ratio of the threshold photoelectron yield, namely 1 : 2.1, i.e. we make the approximation that the ν = 0 cross section and β\(^+_0\) at 24.756 eV to be the same as at 24.564 eV. Thus the measured angular distribution ratio in figure 4(b) is proportional to

\[
\frac{\sigma_{\Omega^+}^{\nu=1}(1+\beta_{\Omega^+}^{\nu=1}\delta_2(\cos \theta))}{\sigma_{\Omega^+}^{\nu=0}(1+\beta_{\Omega^+}^{\nu=0}\delta_2(\cos \theta))} \text{24.756eV}.
\]

(5)

It is evident in figure 4(a) that the ratio distribution is slightly elongated along the polarization direction; from the form of (4) this implies β\(^+\) > β\(^0\), which is primarily due to the differences in lifetimes.

To determine the ratios of (4) and (6), we may assume that the natural asymmetry parameter is independent of the vibrational quantum number. This allows us to use the expression given in [10] based on the earlier work of [12, 41], namely that the inherent or natural asymmetry parameter,
for a non-rotating molecule, which can only be obtained theoretically, is related to the observed or measured value via

\[ \beta_{O^+} = \beta_{O^+}^T \left(1 + a^2 \frac{\omega}{4 + a^2}\right) \]  

(7) 

with \( a = \frac{1}{\tau \omega} \), where \( \omega \) is the rotational velocity of the molecular state and \( \tau \) is its lifetime. Note that when \( \tau \rightarrow \infty \), \( \beta_{O^+} \rightarrow \beta_{O^+}^T/4 \) and as \( \tau \rightarrow 0 \), \( \beta_{O^+} \rightarrow \beta_{O^+}^T \); thus, the effect of rotation is to reduce the inherent asymmetry parameter. We take the equilibrium internuclear separations for the ν = 0 and 1 levels of 1.155 and 1.170 × 10−10 m respectively, from [16] and determine the average value for \( \overline{\tau \omega} \) over a thermal distribution of rotational states, assuming that the gas emerging from the effusive gas source is at room temperature, for specific values of \( \tau_0 \) and \( \tau_1 \). The value of \( \beta_{O^+}^T \) has, to our knowledge, only been determined by Lin and Lucchese [11]. They do not find a significant change in the \( \beta_{O^+}^T \) values with the number of channels they include in their calculations and at threshold \( \beta_{O^+}^T \approx 1.6 \).

Using equations (4), (6) and (7) with \( \beta_{O^+}^T = 1.6 \), \( \tau_0 = 1.2 \times 10^{-11} \) s from the published literature and \( \tau_1 = 6.0 \times 10^{-14} \) s from this work we obtain a completely unacceptable ratio shape in comparison to the data (arbitrarily normalized), as shown in figure 4. We can find no agreement between the observed and theoretical ratio shape for any physically plausible values of \( \tau_0 \) and \( \tau_1 \). Hence, we conclude that there is something seriously amiss in the \( \beta_{O^+}^T \) value suggesting that further work is needed in this regard.

Using \( \tau_0 = 1.2 \times 10^{-11} \) s and \( \tau_1 = 6.0 \times 10^{-14} \) s and keeping them constant results in \( \beta_{O^+}^T = 0.38 \pm 0.07 \) and \( 0.40 \pm 0.05 \) for figures 4(a) and (b), respectively, giving essentially the same \( \beta_{O^+}^T \) from the two different data sets and giving confidence to the approximations made in equation (6). The corresponding \( \beta_{O^+} \) values are 0.10 ± 0.02 and 0.30 ± 0.04 for \( \nu = 0 \) and 1 levels, respectively. These values are in good agreement with \( \beta_{O^+} \approx 0.35 \) observed in the earlier vector correlation study of Lafosse et al [10], indicating that the determination of their vector mapping apparatus function was reliable—despite their stated caution. Although the results in the previous paragraph are obtained from using the ‘best’ values of \( \tau_0 \) and \( \tau_1 \) in equations (4), (6) and (7), we need to consider the effect of using other plausible values. Increasing \( \tau_0 \) makes essentially no difference to the result, since \( \beta_{O^+} \) is close to its limit of \( \beta_{O^+}^T/4 \) for \( \tau_0 \) (see equation (7)). If we take \( \tau_0 \) as \( 6 \times 10^{-13} \) s, the experimental lower limit from [18], we find \( \beta_{O^+}^T = 0.40 \pm 0.07 \) and 0.41 ± 0.06 for figures 4(a) and (b), respectively. If we take \( \tau_1 = 6.9 \pm 0.7 \times 10^{-14} \) s, the consensus experimental and theoretical values from table 2 [16, 18], then we find \( \beta_{O^+} = 0.42 \pm 0.07 \). These values all cluster within error bars of the fit, so the uncertainties in the lifetimes \( \tau_0 \) and \( \tau_1 \) do not significantly affect the value of \( \beta_{O^+}^T \).

4. Summary

In this TPEPICO study we use the high resolution of the threshold channel to define the vibrational level of the \( O^+_2 \) \( c^4 \Sigma_u^+ \) state and examine the angular distribution of the ions, characterized by an angular asymmetry parameter, following DPI. Analysis of the observed asymmetry parameter allows one, in principle, to determine predissociation lifetimes and compare the results with those obtained by other experimental methods, such as deconvolution of the observed energy widths, and with theoretical predictions. To our knowledge, this method is rarely, if ever, used. Recent advances in ion momentum imaging techniques should make this more straightforward in future. We demonstrate that the judicious use of angular distribution ratios not only eliminates potential (and real) systematic errors in the observed angular distributions, but in special cases the need for a time-consuming coincidence experiment can be avoided altogether. Thus the technique we present here has a much wider application to other dissociative ionizing species. This study also highlights the need for accurate and reliable theoretical values of ion asymmetry parameters.

Our analysis of the ratio of the photoion angular distribution of \( O^+_2 (4^4 S) \) produced from DPI of \( O^+_2 \) \( c^4 \Sigma_u^+ (\nu = 0, 1) \) also allows us to place a lower limit on \( \tau_0 \) as \( \approx 1 \times 10^{-12} \) s, corresponding to a width of \( < \approx 1 \) MeV. This work, therefore, supports the experimental findings of [18]. There remains a factor ~20 difference between the experimentally determined lower limit of \( \tau_0 \) and the current predicted values, even with this new experimental approach; narrowing that gap is a challenge for future work. The lack of sensitivity in being able to determine \( \tau_0 \) more precisely, for a given \( \tau_1 \), using this technique is partly due to the small value of the inherent asymmetry parameter \( \beta_{O^+}^T \), for this particular ionic state. We have also determined \( \tau_1 \) as \( 6.0 \pm 0.3 \times 10^{-14} \) s and \( \beta_{O^+} = 0.40 \pm 0.05 \), which is significantly smaller than predicted, \( \beta_{O^+}^T \approx 1.6 \), in agreement with the experimental findings in [10]. Our estimate of the energy width of \( 120 \pm 20 \) meV for the \( \nu = 2 \) level, corresponding to \( \tau_2 = 5.5 \pm 1.0 \times 10^{-15} \) s, is in excellent agreement with the results of recent calculations [17, 24, 25].

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