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Reply to "Comment on 'Coherent interference in the resonant dissociative electron attachment to carbon monoxide' "

Shan Xi Tian[1,*] and Yi Luo[1,2]
[1]*Hefei National Laboratory for Physical Sciences at the Microscale, University of Science and Technology of China,*
Hefei, Anhui 230026, China
[2]*Department of Theoretical Chemistry and Biology, School of Biotechnology, Royal Institute of Technology, S-106 91 Stockholm, Sweden*

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We respond to Nag and Nandi's Comment on our paper [Phys. Rev. A **88**, 012708 (2013)], in which the arguments arise from the data analyses of the angular distributions of O$^-$ produced in the dissociative electron attachments to CO at 10.5 or 10.6 eV although the same technique, anion-velocity time-sliced map imaging, was used. The forward distribution in the O$^-$ image observed by Nag and Nandi arises from the low momentum resolution and distortion in their ion velocity imaging measurements. These artifacts are due to their arbitrary elongation of the ion flight tube and the uncertainty in the size control of the reaction volume.

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In our recent article [1], we observed the completely backward distributions of O$^-$ produced in the dissociative electron attachment (DEA) to CO at 10.0 and 10.6 eV, while some extremely weak O$^-$ signals appeared in the forward direction of the momentum image at 10.5 eV recorded by Nag and Nandi [2]. The difference in the O$^-$ images at 10.6 eV [1] and 10.5 eV [2] leads to Nag and Nandi's comment [3] on the concept "coherent resonance" of CO$^-$ proposed by us [1]. Although the same experimental technique, anion velocity time-sliced map imaging, was used by both of us, some differences between their [4] and our [5] apparatuses are distinct. We believe that these apparatus differences should be responsible for the different observations about the forward distribution of O$^-$.

In Nag and Nandi's work [2,3], the wedge-and-strip anode [4] was replaced with the delay-line hexanode in the anion detector. In our apparatus, the detector was assembled with double microchannel plates and a phosphor screen, providing the higher ion detection efficiency [5]. The central time-sliced images can be obtained in the off-line data analysis [2–4], but we use a high voltage pulse on the last microchannel plate to select anions we are interested in and to record the time-sliced image simultaneously [5]. In our experiments, we should be careful to determine the pulse time position of the central slice. Therefore, we made several slices of the O$^-$ ion Newton sphere at a certain electron attachment energy, and some of them can be found in Fig. 2 of Ref. [1]. All sliced images in Fig. 2(c) [1] consistently showed the completely backward distributions of the fast O$^-$ ion [produced in Process I : $e^- + \mathrm{CO} \rightarrow \mathrm{C}(^3\mathrm{P}) + \mathrm{O}^-$]; while the slow O$^-$ ions produced in Process II [$e^- + \mathrm{CO} \rightarrow \mathrm{C}(^1\mathrm{D}) + \mathrm{O}^-$] were also observed as the central spots in the central sliced image ($t = 0$ ns), but disappeared in the offset sliced images ($t = 40$ and 60 ns) because the Newton sphere of these slow ions is much smaller. Our images are very clear and in the high signal-to-noise ratio, much better than Nag and Nandi's images [2]. In our images, no influences or shades of the wire mesh used in our apparatus were observed.

To obtain a clear ion image, one should pay more attention to the experimental arrangement or design [1,5,6]. In Nandi's design [4], only three electrodes were used for the ion velocity focusing, while nine electrodes were used in our apparatus [1,5] not only for the ion velocity focusing but also the spatial focusing (because of the different ion production positions). It is more flexible to use multiple electrodes for the excellent spatial and velocity focusing [6]. On the other hand, the small size of the reaction volume (less than $2 \times 2 \times 2\,\mathrm{mm}^3$; see Fig. 3 of Ref. [5]) must be guaranteed in the experiments because the spatial focusing is effective only for the limited reaction volume [6], while the reaction volume size was never mentioned in their studies [2–4]. Moreover, the flight tube length was arbitrarily elongated (the length was doubled!) without any improvements of the electrode design in their experiments [2,3]. Therefore, the momentum resolution of their apparatus [2,3] must be seriously lowered although the mass resolution may be enhanced. The images recorded with such a problematic apparatus, of course, are distorted and blurred (see Fig. 2 of Ref. [2]). This is the primary reason that Nag and Nandi observed some extremely weak O$^-$ signals in the forward direction. In Ref. [1], we also discussed the poor momentum resolution in the previous study [7]: "The reaction area in their experiments was not small enough, ..., in other words, many Newton spheres with the different center positions may exist in the ion flights." On the other hand, in their experiments [2,3], the contaminations or the residual gas such as O_2, CO_2, or H_2O in the sample inlet system may contribute to the weak O$^-$ signals in the forward direction. In our experiments, the chamber and the sample inlet system were cleaned by heating and then inspected with the residual mass spectra; no contaminations were found in our imaging measurements.

Nag and Nandi's angular distribution analyses [3] were also problematic. In Fig. 4 of our paper (Ref. [1]), the signals of O$^-$ ion with the kinetic energies in a range 0.35–0.65 eV were selected for plotting the angular distribution and the data analyses. It is obviously questionable that a very wide range of the kinetic energy, 0.10–0.65 eV, was used by Nag and Nandi [2,3]. See Fig. 1(a) of their comment [3]; in that kinetic energy range, the ion signals from Processes I and II are seriously overlapped. A narrower range of the kinetic energy should be more suitable for their data analyses. In our study [1], these two processes were clearly identified in the images and

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[*] sxtian@ustc.edu.cn

there were no ion intensity overlaps in the experimental data fittings.

At last, some progresses about the "coherent resonance" proposed in Ref. [1] should be addressed. Although we discussed this concept in relation to quantum scattering, the formation of a coherent resonance of the electron-molecule system is quite similar to the coherent interference of vibrational states by the ultrafast laser pulse. If a wide band femtosecond laser pulse covers serval close-lying vibrational eigenstates, those eigenstates are thus coherently superposed to give constructive or destructive interferences [8]. In our study [1], the close-lying resonances can be entangled by the broad electron pulse (200 ns width and 0.5 eV energy spread). Our experimental study on the DEA to CO has been extended to the higher energies (11.3–12.6 eV), and the completely backward distributions of O^- were observed again, demonstrating that the so-called coherent resonance also plays the important role in Process II [9]. In Fig. 1, the O^- sliced image recorded at 12.1 eV is shown, where the backward O^- ions are produced in Process II and no forward signals are observed. More results and discussions can be found in Ref. [9].

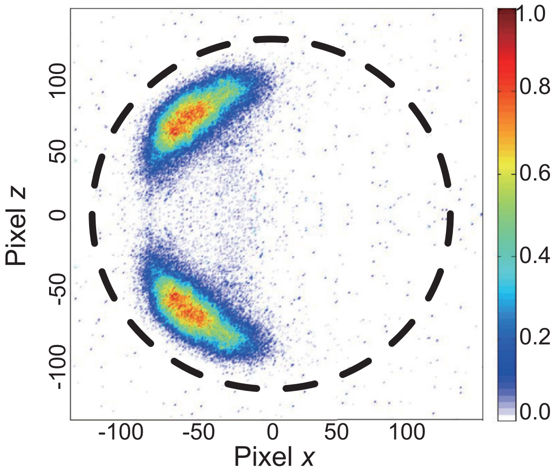

FIG. 1. (Color online) The sliced image of O^- ions produced via Process II recorded at 12.1 eV, while the signals of Process I are out of the detector (the detector edge is shown with a broken circle) due to the much higher kinetic energy of the ion. The electron incident direction is from left to right and through the image center.

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