Revealing the nuclear rearrangements of complex, polyatomic molecules during chemical reactions is essential for understanding their elaborate molecular mechanisms behind. In order to achieve this, it is highly desirable to record a series of snapshot structures of a reacting molecule from the reactant, all the way down to the product with high time resolution. Nevertheless, it has been a significant, technical challenge to observe structural events occurring on a timescale of the nuclear motions of molecules, i.e., femto-to-picosecond timescale. In order to capture nuclear rearrangements of "reacting" molecules on such an ultrafast timescale, the applicant developed time-resolved impulsive stimulated Raman spectroscopy (TR-ISRS) using sub-7-fs pulses, and **realized observation of structural dynamics occurring on the femtosecond timescale with a broad detection window ranging from the THz to >3000-cm^{-1} region and sensitivity down to <1 μOD** [***Rev. Sci. Instrum.* (2016)**]. Furthermore, by taking advantage of these exquisite capabilities, the applicant studied primary photoreaction processes of photo-responsive proteins, and revealed the femtosecond structural dynamics that are essential to drive their functions.

Specifically, the applicant unveiled ultrafast rearrangement of the hydrogen-bond structure around the chromophore of Photoactive Yellow Protein (PYP) for the first time, which is completed within just a few hundreds of femtoseconds after photoexcitation. In addition, using TR-ISRS and quantum chemical calculation, the applicant fully characterized the vibrational structure of the first ground-state photocycle intermediate of PYP, revealing a substantially-twisted cis conformation of the chromophore. Actually, the structure of this intermediate had been under the intense debate because two time-resolved X-ray diffraction studies using the state-of-the-art synchrotron radiation source reported two different structures. However, **the applicant's unambiguous data finally settle this controversy, and demonstrated that TR-ISRS is a very powerful method for revealing ultrafast, small, but significant structural changes inside photoreceptor proteins, which even the state-of-the-art X-ray crystallography cannot resolve** [*Nat. Chem.* **2017**]. The applicant also addressed the role of the coherent low-frequency vibration of the chromophore on the excited-state proton transfer (ESPT) reaction of Green Fluorescent Protein (GFP), which is an essential molecular mechanism behind its bright green fluorescence. A previous femtosecond stimulated Raman study of GFP proposed that a coherent low-frequency vibration of the chromophore periodically modulates its hydrogen-bond strength with the nearby water and thus facilitates the ESPT, giving a big impact on the community. However, **the applicant's TR-ISRS data clearly demonstrated that the low-frequency motion does not play a major role on the ESPT, and instead, the applicant proposed a new ESPT mechanism** [*J. Am. Chem. Soc.* **2016**].

The TR-ISRS spectrometer that the applicant has developed represents an ultimate form of the time-resolved Raman spectroscopy. With this technique, the applicant significantly advanced our understanding on the primary structural events of the photo-responsive proteins that trigger the subsequent chain of reactions to finally achieve their functions. These achievements by the applicant opens a new avenue for the investigation of chemical reaction dynamics in complex molecular systems. The applicant is now further expanding TR-ISRS to a new multi-dimensional Raman spectroscopy that can characterize the shape of reactive potential energy surfaces [*submitted*].