**John C. Wright**

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July, 2024

Dear Editor,

We enclose a manuscript entitled *Coherent Hyper-Raman Four Wave Mixing Vibrational Spectroscopy,* authored by Ryan P. McDonnell, Daniel D. Kohler and John C. Wright for consideration as a publication in *The* *Journal of Chemical Physics* as part of the Y. Ron Shen Festschrift.

The corresponding author is:

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Four wave mixing (FWM) spectroscopies are largely known for their ability to dissect vibrational anharmonicity in large and small molecular species. These methods resolve anharmonic coupling though infrared (2D-IR) and infrared/Raman (Doubly Vibrationally Enhanced) pathways. These methods were based upon coherent anti-Stokes Raman spectroscopies (CARS) developed in the 1970 and 1980’s. Similarly, three wave mixing (TWM) methods resolve interfacial vibrational spectroscopy and dynamics through infrared/Raman pathways (sum frequency generation). A seldom used type of transition which could increase the specificity of nonlinear spectroscopy are hyper-Raman transitions. However, unlike CARS, the coherent analogue of pure hyper-Raman spectroscopy is a six wave mixing technique, which is virtually impossible to resolve in the laboratory due to lower order, four wave mixing cascades that complicate output. The only example of an infrared/hyper-Raman type method was developed in our laboratory decades ago to demonstrate the feasibility of four wave mixing involving solely vibrational transitions but has not been investigated in detail for over twenty years.

Very recent experiment work from our laboratory and Mischa Bonn’s laboratory has made it clear that hyper-Raman based FWM spectroscopies are present in infrared/Raman FWM spectroscopies. To this end, we have investigated the parameters which drive nonlinear output in the infrared/hyper-Raman type spectroscopies and identified gross selection rules. The spectroscopy has been called hyper difference frequency generation (HDFG), due to its similarity to difference frequency generation. We have shown that the HDFG methods provide output for any harmonically allowed, infrared active vibration. Since the methodology is only dependent upon a single quantum coherence, this makes HDFG a potential probe of single quantum coherences in isotropic media without need for anharmonicity. We have identified methods for using FWM to quantify the hyper-Raman hyperpolarizability, negating the need for complex spontaneous hyper-Raman experiments.

The major innovations of our paper are:

1. Identification of Singly Vibrationally Enhanced (SIVE) spectroscopy as the coherent four wave mixing analogue of hyper-Raman spectroscopy. This bypasses the need for six wave mixing techniques
2. We show how quantitative analysis of SIVE spectra can resolve the hyper-Raman polarizability *via* the interferometric technique developed by Levenson and Bloembergen.
3. We demonstrate that SIVE spectroscopy is, on average, as bright as sum frequency generation spectroscopy, making it a feasible method for interpreting isotropic spectra of most vibrational species.

We believe this manuscript highlights the versatility of mixed time-frequency domain methods as a probe of molecular structure and will be of great interest to the readership of *The Journal of Chemical Physics*. This work has a direct impact on the development of multidimensional spectroscopies and provides new methods for investigating vibronic coupling in molecular species. We believe this work will encourage the implementation of mixed time-frequency domain methods for probing noncovalent interactions and ultrafast dynamics in material and biomolecular systems, chemical reactions, and probing vibronic coupling in complex molecular systems.

Sincerely,

A close-up of a black handwritten letter

Description automatically generated

John C. Wright

Andreas C. Albrecht Professor of Chemistry

University of Wisconsin - Madison

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P.S. We suggest the following reviewers:

**Prof. Artem A. Bakulin**

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Reason: Prof. Bakulin is an expert in the application of infrared and infrared-visible spectroscopies to a variety of unique chemical and materials systems.

**Prof. David A. Blank**

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Reason: Prof. Blank is an expert in the application of mixed vibrational/electronic spectroscopies.

**Prof. Jon P. Camden**

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Reason: Prof. Camden in an experiment in resonance hyper-Raman scattering spectroscopy.

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**Prof. Minhaeng Cho**

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Reason: Prof. Cho is an expert in the theory of the coherent multidimensional spectroscopies discussed in this manuscript.

**Dr. Paul M. Donaldson**

Senior Scientist

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Reason: Dr. Donaldson is a pioneer and expert in the application of coherent Raman spectroscopies to biomolecular samples.

**Dr. Maksim Grechko**

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Reason: Dr. Grechko is an expert in the design and application of the coherent multidimensional spectroscopies discussed in this manuscript.

**Prof. Anne Myers Kelley**

School of Natural Sciences

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Reason: Prof. Myers Kelley is a pioneer and expert in four wave mixing spectroscopy and the application and theory of resonance Raman and hyper-Raman spectroscopy to condensed phases.

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**Prof. Patrick Vaccaro**

Department of Chemistry

Yale University

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Reason: Prof. Vaccaro is an expert in the application and theory of coherent four wave mixing spectroscopies.

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**Prof. Lawrence D. Ziegler**

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Reason: Prof. Ziegler pioneered gas phase resonance hyper-Raman spectroscopy.