Communicating Research to the General Public

The WISL Award for Communicating PhD Research to the Public launched in 2010, and since then over 100 Ph.D. degree recipients have successfully included a chapter in their Ph.D. thesis communicating their research to non-specialists. The goal is to explain the candidate's scholarly research and its significance—as well as their excitement for and journey through their area of study—to a wider audience that includes family members, friends, civic groups, newspaper reporters, program officers at appropriate funding agencies, state legislators, and members of the U.S. Congress.

WISL encourages the inclusion of such chapters in all Ph.D. theses everywhere, through the cooperation of PhD candidates, their mentors, and departments. WISL offers awards of $250 for UW-Madison Ph.D. candidates in science and engineering. Candidates from other institutions may participate, but are not eligible for the cash award. WISL strongly encourages other institutions to launch similar programs.

WISL
Wisconsin Initiative for
Science Literacy

The dual mission of the Wisconsin Initiative for Science Literacy is to promote
literacy in science, mathematics and technology among the general public and
to attract future generations to careers in research, teaching and public service.

Contact: Prof. Bassam Z. Shakhashiri

UW-Madison Department of Chemistry

bassam@chem.wisc.edu

www.scifun.org

The Study of Nitrogen-Containing Molecules of Astrochemical Importance using Rotational Spectroscopy and Computational Chemistry

By

Maria A. Zdanovskaia

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

(Chemistry)

At the

UNIVERSITY OF WISCONSIN – MADISON

2022

Date of final oral examination: January 20, 2022

The dissertation is approved by the following members of the Final Oral Cimmittee:
Robert J McMahon, Professor, Materials, Organic, and Physical Chemistry
R. Claude Woods, Professor, Physical Chemistry
Etienne Garand, Professor, Physical and Analytical Chemistry
Thomas Brunold, Professor, Inorganic and Physical Chemistry, Chemical Biology

Chapter 9:

The Use of Rotational Spectroscopy in Studying Molecular Properties of Several Molecules

This chapter is intended to briefly explain to a non-scientifically trained audience what rotational spectroscopy is, what it is used for, and how it has been applied to studying several molecules in the research of a graduate student at the University of Wisconsin – Madison. Although some types of spectral analysis are quite frequently used across chemistry disciplines, the study of rotational spectra discussed herein is a relatively niche field that even professional chemists from other chemistry sub-disciplines sometimes find perplexing. Nevertheless, I recognize the importance of all people – whether trained in a scientific field or not – being exposed to and having an appreciation for what research and science are, so I attempt herein to share my graduate school research with a general audience.

The majority of my thesis is based on analyzing how gas-phase molecules rotate. In the gas phase, molecules are far apart, so they experience fewer collisions or interactions than when they are in the liquid or solid phases. Studying the rotation of a molecule can actually provide some fairly detailed information about the molecules because of what we understand about physics. Consider a round ball, an American football, a Frisbee, and a hammer (Fig. 9.1). The round ball is symmetric all around, so it rotates the same way no matter how you spin it when you throw (Fig. 9.1a). Typically, footballs are thrown to spin around their long axis (Fig. 9.1b), because that makes it easiest to aim and throw farther, but you can imagine spinning it end-over-end, and that feels different. A Frisbee is typically spun along its edge (Fig. 9.1c), but you can also imagine rotating it end-over-end. Because the hammer has no roundness or symmetry to it any way you look (Fig. 9.1d), it spins differently in all directions, whether you throw it by swinging the handle up/downward, sideways, or by holding it like a javelin and spinning the handle. The shape of the object and distribution of mass affect how the object rotates as it flies.

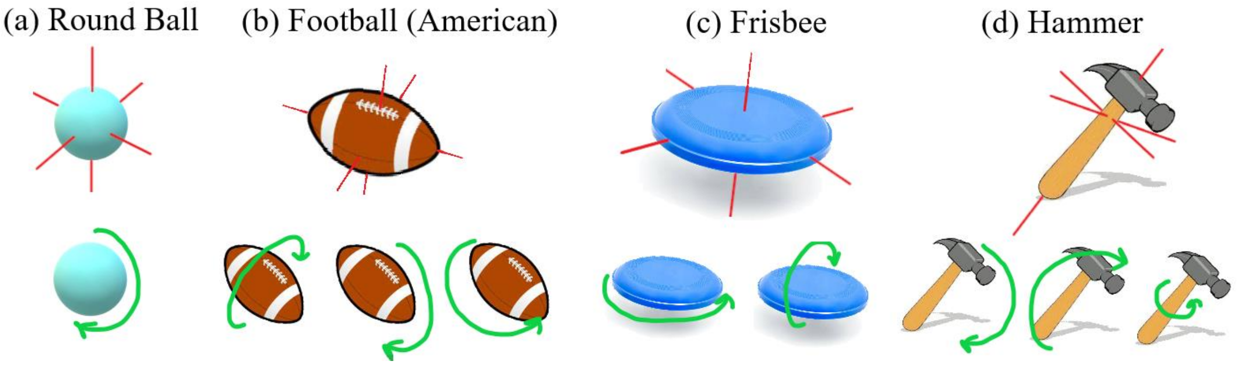


Figure 9.1. A (a) round ball, (b) American football, (c) Frisbee, and (d) hammer with red lines showing the axes around which they can rotate and green arrows representing such rotation.

But obviously, we can't pick up a molecule with tiny tweezers, throw it, and watch it spin (that's what you would see in a "Stock Photos of my Profession" image), so we use a spectrometer. In general, spectroscopy is the study of matter by measuring how it interacts with or emits light. For our experiments, we fill a chamber that has windows on either end with the gaseous molecules. Then, we send different energies of light through the chamber and monitor the light energy that comes out the other end. Molecules have different, discrete rotational energy levels, meaning the molecule has to encounter exactly the right amount of energy to transition from rotating at a lower energy level to rotating at a higher energy level. And all of the molecules of the same type share the same energy levels. Therefore, when we reach just the right energy of light being put into the chamber, the molecules absorb that light to undergo the rotational energy transitions, that light energy does not come out the other end of the chamber, and we take note. It results in a plot that looks like the one below (Fig. 2). This type of spectroscopy is called *Rotational Spectroscopy.*

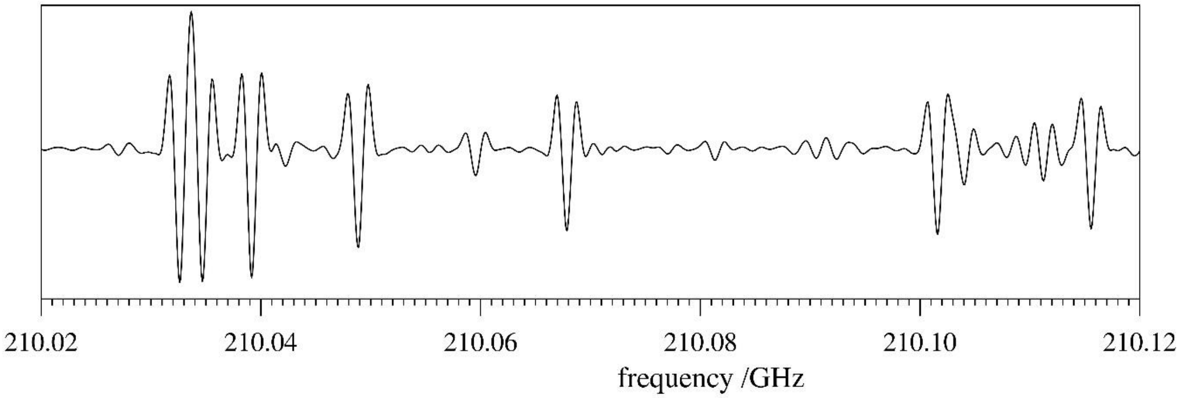


Figure 9.2. A small segment of the experimental rotational spectrum of the molecule benzonitrile. The numbers on the *x*-axis are a way of describing the energy of light that caused the rotational transition. The large downward peaks belong to the non-vibrating benzonitrile molecule, while many of smaller visible peaks belong to benzonitrile as it vibrates in various ways.

We then use very complex maths to assign the peaks in the spectrum to rotational transitions of the molecule, which allows us to determine a series of constants, called *rotational* and *centrifugal distortion* constants. There are three *rotational* constants, and these have to do with how mass is distributed in 3D space, along three axes (as in Fig. 9.1). *Centrifugal distortion* constants have to do with how the shape of the molecule is affected by spinning and by the bonds between atoms. Collectively, the rotational and centrifugal distortion constants are called *spectroscopic constants*. Knowing the energies associated with different ways that a molecule spins and the aforementioned constants allows us to determine very precisely some properties, such as the structure – what masses (that is, what elements) are in what locations within the molecule. Now imagine a fun Jell-O jiggler shape or a pancake instead of a frisbee. Even though it is one unit, it wiggles and bends. Molecules also wiggle (referred to as “vibrate”), and they vibrate while they are rotating as they fly, which affects how they rotate. (The reader should feel free to make fun Jell-O jiggler shapes at home and try throwing them around. You probably won’t learn much, and they are too heavy to be a good analogy to molecules, but you’re likely to laugh some.) By analyzing the rotational transitions of vibrating molecules, we can get information on how molecular vibration interacts with their rotation.

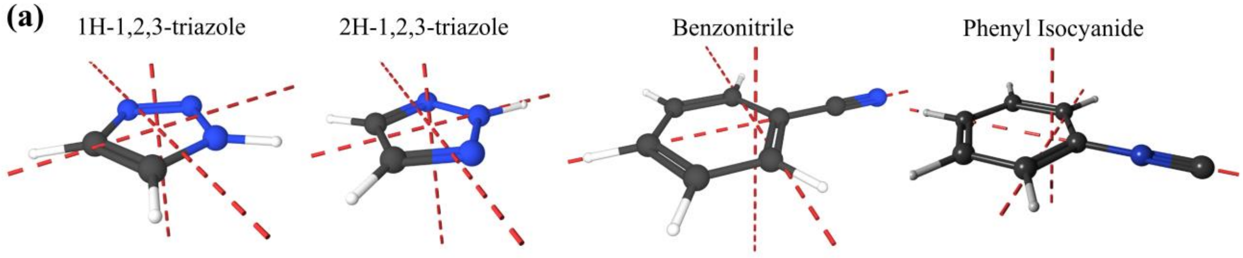
My work also employs a substantial amount of computational chemistry, which is a sub-discipline of chemistry where in chemists use known data and complex math to try to model and predict molecular properties. While these predictions are not spot-on, they are close enough to help us get started analyzing a molecule's rotational spectrum and differentiating transitions from different types of molecular vibrations. Some high-level calculations also provide predictions of quantities we cannot measure experimentally, and these are used to obtain very precise molecular structures. For example, these calculations can help us predict the change to the *rotational* constants that occurs when a molecule vibrates for *all* of the vibrational modes. We cannot measure this difference experimentally for all vibrations, because current technology is not sufficiently sensitive to observe all vibrational modes.

When we begin analyzing a molecule's rotational spectrum, we use predictions of its spectroscopic constants to predict where we will find its transitions in our spectrum. Typically, the predictions are close enough to get us in the neighborhood of where the transitions actually appear. Similarly, once we have analyzed the molecule's base spectrum, we can use the predictions of how vibration affects the rotational constants to find the first few transitions of a vibrational mode. When we determine a molecular structure from a molecule's rotational spectrum, we need to address the fact that the molecule that we observe is never perfectly still – the shape that we observe is affected by the energy it has and the motions it is undergoing. In these cases, computational chemistry predicts numerical values of how much the observed rotational constants are affected by these factors so that we can correct for them.

It is reasonable to ask, if we cannot pick up individual molecules and use them as tiny projectiles, why would we care about their structures or rotations? The structure is important, because it provides other information about the molecule, such as how it will interact or react with other molecules, and that knowledge can be used in designing molecules with targeted purposes. Think, for example, about a topic that has unfortunately drastically affected the world in the past couple of years (2020 – 2022): COVID-19. Knowledge of the structure of the SARS-CoV-2 spike protein enabled development of certain vaccines against it, and each new strain is noted with the number of mutations (changes) it has, which can affect how it interacts with our bodies and existing vaccines. Knowledge of a structure is the basis for knowledge of its interactions.

It also turns out that rotational spectroscopy is a very powerful investigative tool. There are very few probes that can be stuck into the exhaust of a jet engine, but the exhaust can be rigged to go into a spectrometer setup, so we can analyze what comes out. Even fewer probes (zero) can be sent to distant regions of the universe and send information back to Earth about the types of molecules that are out there in a timely manner. It turns out, however, that the energies of light that reach Earth from distant stars include those that cause rotational transitions. Since the rotational spectrum of a molecule is unique, if we know how the spectrum looks from measuring it in the lab, we can match up that picture to the spectrum we're receiving from space and identify molecules that exist in other galaxies or on other planets and moons. As a result, we can begin to infer the types of reactions that might be going on in an environment that, unlike Earth, may be extremely cold or may be exposed to much more intense star radiation. By learning more and more about the molecules and reactions out there, we may be able to piece together how living organisms came to be.

In my thesis, I studied several molecules. Several of these are represented in Fig. 9.3: different-colored balls represent atoms of different elements, and the connecting sticks show which atoms are bonded to one another. Some of the molecules are relatively pancake-shaped (*e.g.*, 1H-1,2,3-triazole, 2H-1,2,3-triazole, phenyl isocyanide, and benzonitrile, Fig. 9.3a) and some that are more like a hammer (*e.g.*, *E*-1-cyano-1,3-butadiene, Fig. 9.3b).



(b) *E*-1-cyano-1,3-butadiene

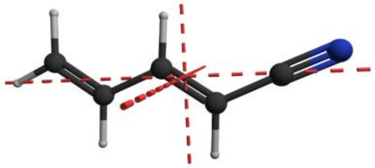


Figure 9.3. Several examples of (a) oblong pancake-like and (b) hammer-like molecules analyzed by rotational spectroscopy. Balls of different colors represents atoms of different elements, and sticks show which atoms are bonded to one another. All examples are shown with 3D axes.

As a result of analyzing the rotational spectra of 1H-1,2,3-triazole (pronounced “try-uh-zole”) and 2H-1,2,3-triazole, we have been able to determine highly precise structures for these two molecules. The bond distances in units of Angstroms (one ten-billionth of a meter) and bond angles in degrees are provided in Fig. 9.4. While these molecules do not naturally occur in plants or animals on Earth, researchers have found that they can effectively mimic certain biological functions,[1,2] and molecules containing a 1,2,3-triazole core are being used in a variety of pharmaceutical applications.[3]

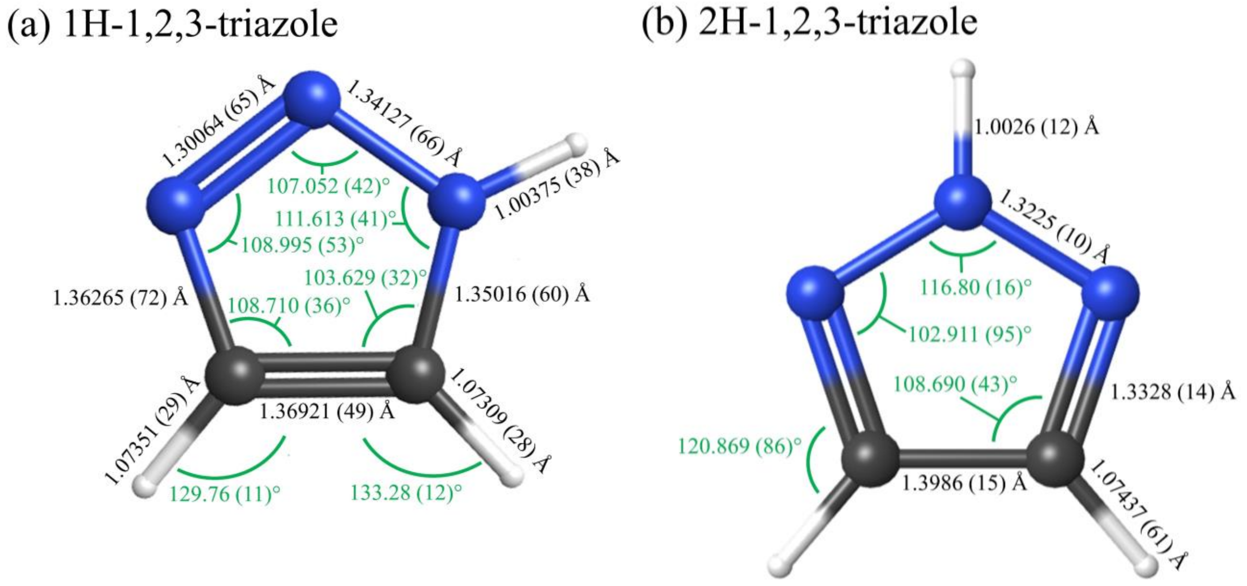


Figure 9.4. (a) 1H- and (b) 2H-1,2,3-triazole structures with bond distances marked in black text in units of Angstroms and bond angles marked in green text in degrees. Values in parentheses are values of uncertainty in the last two digits of the parameter value shown.

Additionally, our analysis provides radioastronomers (astronomers who study the composition of space using spectroscopy equivalent to that which we use) with the spectroscopic constants necessary to accurately model the 1,2,3-triazoles' rotational spectra across a wide range of frequencies, so the molecules can be identified in space or on other planets.

The rotational analysis of benzonitrile (Fig. 9.3a, pronounced "ben-zoh-night-rile") similarly yields highly accurate spectroscopic constants that can be used to identify the molecule and its vibrational modes. The vibrations of benzonitrile interact strongly with its rotation, resulting in what are called Coriolis and Darling-Dennison couplings. There is no good way to imagine the effect of these phenomena on a pancake, but what it means is that some types of rotation take more energy than they would without the interaction, while others take less energy than they would without the interaction. By measuring these interactions and energy shifts, however, we can determine how much more or less energy one mode of vibration takes than another mode. The mode of vibration that takes the least energy to occur in benzonitrile is called

ν_{22} (pronounced "gnu twenty-two") and is the up-and-down wagging motion of the two bonded atoms sticking out from the ring (Fig. 9.5a). The next vibrational mode, ν_{33}, is the side-to-side wagging of the same group (in a motion perpendicular to the up-and-down wag). We also analyzed stronger versions of these vibrations (labeled $\nu_{22} = 2$, $\nu_{22}+\nu_{33}$, and $2\nu_{33}$), and two more complex vibrational modes: ν_{21} looks like a dragon flapping its "wings" in the ring part of the molecule and arching its "neck" (Fig. 9.5b), and ν_{15} looks like a wiggle of the ring structure (Fig. 9.5c), where atoms in the "wings" of the ring structure rise and fall such that adjacent atoms move in opposite directions and atoms across the ring from one another move in the same direction.

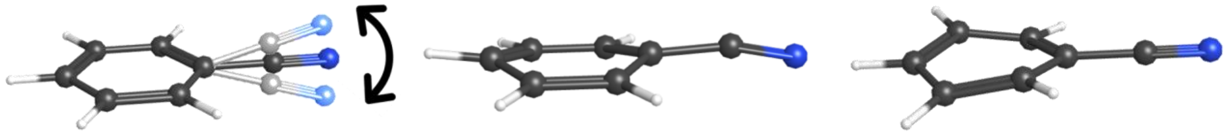

(a) ν_{22} (b) ν_{21} (c) ν_{15}

Figure 9.5. (a) Representation of the up-and-down wagging motion of benzonitrile that is labeled ν_{22}, and distortions of the molecule in motions of (b) ν_{21} and (c) ν_{15}.

Combining our rotational data with infrared spectra (spectra that use higher energies of light than rotational spectra in order to observe molecules transition from one vibration to another), we were able to determine with high precision the energies of several vibrational modes. These energies are shown in Fig. 9.6 in units of wavenumbers (cm^{-1}; higher numbers correspond to higher energies). These measurements set benchmarks for computational chemists to test their ability to accurately predict vibrational energies and can be used (*via* mathematical relationships between temperature and spectral intensity) to estimate temperatures in environments where we cannot send a physical thermometer (such as far-away galaxies).

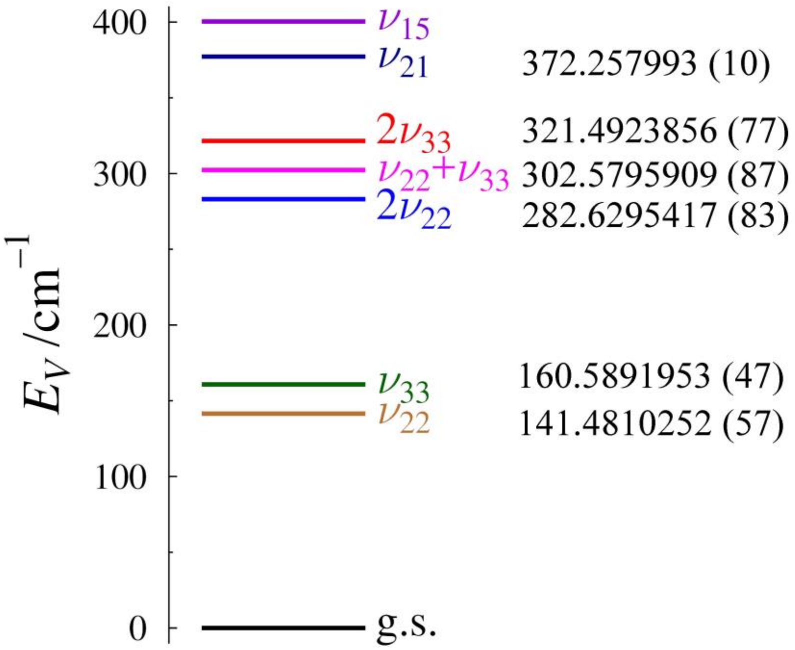


Figure 9.6. Energies of vibrational modes analyzed *via* rotational and infrared spectroscopy in wavenumbers (cm^{-1}). Values in parentheses are the uncertainty value in the last two digits of the corresponding energy value. The "g.s." state (the ground state) is the non-vibrating molecule.

The main information gained by studying *E*-1-cyano-1,3-butadiene (Fig. 9.3b, pronounced "EE-one-sigh-an-oh-one-three-byu-ta-die-een) is the set of spectroscopic constants describing the molecule's rotational spectrum. This is important because the molecule is an excellent candidate for being sought in space. Identifying this molecule in space can help us learn what type of chemistry is occurring in that region and find links to other molecules of interest, which have the same atoms arranged in a different shape. Prior to this work, there were no spectroscopic constants available for the molecule. Therefore, by sharing our analysis with the broader astrochemical community, we have provided the means to seek this molecule in space and learn about that extreme environment that is unlike any conditions we, ourselves, experience on Earth.

Just as many people enjoy various forms of art, music, watching shows, or reading books, it is possible to enjoy science – doing it or appreciating the work others have done. Personally, I enjoy both. While my undergraduate degree is in psychology – a day-to-day useful and applicable branch of science – and mathematics, for its intricacy and beauty (as well as its daily utility), I chose to pursue chemistry for my graduate degree because it was so satisfying. For me, psychology is kind of like whipped cream – you can incorporate that into anything, but you won't be full with just whipped cream. Psychology is too complex – there are simply too many factors at play – to have widely applicable, good models to understand behavior. The understanding of molecular structures and models used in chemistry, on the other hand, enable both prediction and rationalization of much reactivity, and that is satiating. It's also fun. Analyzing spectra is like playing a video game or a jigsaw puzzle (depending on the type of spectrum), and the ability to predict how a reaction will turn out and get the anticipated result feels good, too. Even those who do not practice chemistry, however, can appreciate it, just like people who do not consider themselves musicians can still enjoy music. To this end, it is important that the scientific community continue to share with the broader public the beauty of their research.

1. E. Bonandi; M. S. Christodoulou; G. Fumagalli; D. Perdicchia; G. Rastelli; D. Passarella, "The 1,2,3-triazole ring as a bioisostere in medicinal chemistry," Drug Discovery Today *22*, 1572-1581 (2017).
2. I. E. Valverde; A. Bauman; C. A. Kluba; S. Vomstein; M. A. Walter; T. L. Mindt, "1,2,3-Triazoles as Amide Bond Mimics: Triazole Scan Yields Protease-Resistant Peptidomimetics for Tumor Targeting," Angew. Chem. Int. Ed. *52*, 8957-8960 (2013).
3. K. Bozorov; J. Zhao; H. A. Aisa, "1,2,3-Triazole-containing hybrids as leads in medicinal chemistry: A recent overview," Biorg. Med. Chem. *27*, 3511-3531 (2019).