1. **Project Title (maximum 150 characters): \***

Life in the universe: a quantum chemistry point of view

1. **Executive Summary (maximum 1300 characters): \*** The Executive Summary should briefly address the following questions:
* (a) What specific questions will your project answer?
* (b) What activities will you carry out to answer those questions?
* (c) Why is this project needed?
* (d) What concrete deliverables will you produce by the end of the project?
* (e) What impact will your project have?

How did life on earth form? Are we alone in the universe? These questions are central to science. **If chemical evolution occurs in the interstellar medium (ISM) to form life’s building blocks, then it is possible that life is a universal phenomenon.** An understanding of the chemistry occurring in the ISM and prebiotic molecule formation is essential to our understanding of life. Quantum chemistry is essential for the study of interstellar chemistry; however, it lacks the ability to model large molecules in an electronically excited state. We propose the development of new theoretical capabilities within quantum chemistry that will enable molecular modeling in excited electronic states due to interactions with UV radiation, a process crucial to interstellar chemistry. By the end of the project, we will have developed new capabilities within the framework of ensemble density functional theory (DFT) that will enable modeling reactions of large molecules in an excited state. We will first use small systems to benchmark the new method and prove its accuracy. The impact is expected to be tremendous, as for the first time, we will be able to *fully* study the possible formation of life’s building blocks in different outer space environments.

1. **Project Description (maximum 4000 characters including everything): \*** Please describe the work/activities you will undertake in your project.

In environments like molecular clouds, where stars are born, molecular formation still puzzles scientists. The mechanism behind the formation of new molecules can be considered via ‘bottom-up’ or ‘top-down’ chemistry. The bottom-up mechanism describes molecules as being gradually built up from smaller building blocks. This mechanism is used to model reactions taking place in different areas of the ISM and provides relevant astrochemical and astrobiological insights. Quantum chemistry is used to illuminate reactions’ bottom-up mechanisms and provide molecular level understanding of chemical processes (Bera et al. 2017). On the other hand, in the ISM, molecules are speculated to be synthesized via a top-down mechanism (Candian, Zhen, & Tielens 2018). According to this mechanism, large aromatic molecules can form in the stellar ejecta of asymptotic branch stars. Polycyclic Aromatic Hydrocarbons (PAHs) become highly electronically excited due to interactions with UV radiation. Since they are highly excited, they fragment into smaller molecules via the top-down mechanism. Excited electronic states are likely to play a crucial role in the chemistry of the ISM not only by the top-down mechanism but also from the bottom-up approach. It has been shown that excited oxygen atoms can further react via insertion reactions to form more complex organic molecules. The photochemistry that occurs due to the exposure of ices to UV radiation can result in the formation of complex organic molecules, such as amino acids (Bergner et al. 2017). From a theoretical point of view, modeling excited electronic state potential is much more challenging than modeling the ground state potential. The goal of this proposal is to develop a new method that will be both accurate and computationally feasible for studying large molecules.

The limitation in the study of fragmentation of molecular systems is that DFT, which is in many cases the method of choice, cannot reliably model fragmentation from an excited state due to the lack of multi-reference character in the approximate exchange correlation (XC) functionals. We will use the formalism of ensemble DFT to study excited states, but challenges arise because traditional XC functionals are insufficient in the ensemble treatment. To overcome this limitation, we will use XC functionals from the generalized Kohn Sham (GKS) formalism. We will focus on answering the following questions:

* Which features of the exact XC functional are important in ensemble treatment to obtain multi-reference character?
To overcome the lack of multi-reference character in traditional DFT, we are using ensemble DFT. As ensemble DFT uses the energy at fractional occupation numbers, the energies at each fractional occupation should be correct. The energy of the exact XC functional as a function of occupation number is linear, a feature that is not obeyed using traditional functionals. However, this can be reconstructed with GKS formalism using range-separated hybrid functionals (Kronik et al. 2012). We will study several range-separated functionals and benchmark them with respect to high level *ab-initio* methods such as CASSCF and CASPT2 on small molecular systems to verify that we are restoring the multi-reference character. The effect of other exact conditions, such as behavior at fractional spins, will also be tested on model systems.
* How can we model the evolution of systems over time? We will incorporate the ensemble DFT together with *ab-initio* molecular dynamic (AIMD) simulations to study the evolution of molecular systems over time. This will provide the predictive ability to determine which molecules form or break, and under which conditions and starting points.

Equipped with the tools above, we will study the formation of prebiotic molecules on different ice compositions doped with small aromatic molecules. From these results, we will be able to predict astrobiologically important routes for molecular formation.

**4. Statement of significance (maximum 1,300 characters including everything)**

Describe the current conditions in the field(s) relevant to the project, identify the problems that the project will address, and articulate the specific opportunity that your project presents.

A large multidisciplinary effort is underway to study the formation of life’s building blocks. This involves astronomical measurements and lab experiments to mimic the conditions in outer space, and quantum chemistry models that study the underlying molecular mechanisms. NASA will launch its most powerful telescope, the James Webb Space Telescope (JWST), on 11/21, which is expected to greatly expand our current knowledge. Theoretical calculations are crucial as they provide insights into the unique chemistry that occurs in outer space and can guide astronomers in their search for new molecules, while revealing the detailed mechanisms of their formation.

To fully and accurately model the chemistry in the ISM, one needs to be able to model photochemical reactions. We will develop methods that enable the study of excited state reactivity and significantly advance the ability to model chemistry in outer space. This is expected to have a significant impact in the astrochemistry, astronomy, and astrobiology fields, as well as in the chemistry community in general, as the interaction of light with matter drives many chemical processes.

**5. Outputs (1300 characters)** Outputs (sometimes called "deliverables") are important events and work products that your Project activities (described in #3, above) will lead to, and which are necessary in order for you to make progress towards your proposed Outcomes (#6 below). Please provide a list of the outputs you intend to produce.

By the end of the project, we will be able to model reactions and molecular fragmentation in different excited electronic states, processes that are at the core of interstellar chemistry and crucial to understanding the formation of prebiotic molecules in ice environments.

* We will compare the performance of range-separated hybrid functionals used in an ensemble formalism to the performance of traditional functionals and also to accurate *ab-initio* methods, in order to examine which properties of the exact XC are crucial for modeling multi-reference character.
* The novel approach will be programed into Qchem software, of which Dr. Stein is one of the developers, to be used in *ab-initio* molecular dynamics. This will enable broad use of the newly developed method so that other groups can use it.
* We will perform AIMD simulations that will model conditions of different interstellar environments and provide insights into feasible astrobiological paths.

**6. Outcomes (1300 characters)** Outcomes (sometimes called goals, results, or impacts) are the specific and identifiable changes that you expect your Outputs will bring about (or contribute to bringing about) within 5 years of your project's end date. These should describe what the success of your project would look like. Please provide a list of the outcomes you expect to come about as a result of your outputs.

* Within five years of the project’s end date, the ability to accurately model excited state reactivity for large molecular systems will be computationally feasible and available via commercial quantum chemistry software, to expand utilization.
* We will be able to predict which prebiotic molecules can form in the known conditions of molecular clouds.
* We will have the ability to compare the feasibility of different suggested mechanisms, such as ‘top-down’ and ‘bottom-up’.
* We will closely collaborate with experimental groups and guide their search for prebiotic molecules, as we will be able to predict the likelihood of the formation of different molecules in different areas.
* The ability to accurately model excited state systems will expand the scope of quantum chemistry not only in astrobiological applications, but also in general chemistry and material science, as the interaction of light with material is central to these sciences as well.

**7. Capacity of success (1300 characters)** The Capacity for Success should explain why your team and/or organization is positioned to be successful in this project.

Dr. Tamar Stein is a specialist in quantum chemistry, and throughout her career has developed new methods to overcome the limitations of available tools and successfully broaden the field’s domain. Her work has made a significant impact, as expressed by the considerable number of journal citations she has amassed (5060). Dr. Stein developed new methods which are widely used, including an approach to overcome limitations in Density Functional Theory (DFT). This enables calculating charge-transfer states within DFT, a problem that was previously considered to be outside the scope of DFT. Additionally, she developed a new wave function method that is capable of accounting for multi-reference character in electronic systems. During her time as a postdoctoral fellow, Stein was a part of the Ames Astrobiology Center at NASA and is recognized as an expert in the fields of astrochemistry and astrobiology. Dr. Stein, with her in-depth knowledge of both fields, is intimately aware of the challenges in modeling astrochemical systems but has the proven capabilities to develop new methods for overcoming those limitations.

**8. Relation to Sir John Templeton's Donor Intent (maximum 1000 characters): \***

As the motto for his foundation, Sir John Templeton said, “How little we know, how eager to learn.” Questions surrounding the formation of life in the universe are well-described by this statement. Very little is known about how life is formed and where in the universe this happens. However, we are very eager to learn! These questions have intrigued mankind and ignited the imagination, not only of scientists, but also artists and authors (as is evidenced by the large number of science fiction books). We believe that the suggested project will significantly advance our understanding in this field, as it will shed light on the basic formation steps of life’s building blocks.

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**5. Project Relationship to Previous Grants (2000 characters): \*** To the best of your knowledge, is the work of your proposed project similar to, a continuation of, or an expansion of an active or completed grant you or your organization received from either the John Templeton Foundation, the Templeton Religion Trust, or the Templeton World Charity Foundation? If "Yes," please explain your answer in the text box. Be sure to include the previous project's Title, Grant ID#, Grant Amount, end date, and a very brief synopsis of the project activities

 Dr. Tamar Stein is a young, pre-tenured PI who wants to use her expertise to answer some of humanity’s critical and significant questions. This is her first grant application with the Templeton foundation.

**13. History with the Foundation (maximum 1000 characters): \*** Please describe how you or any members of your team came to learn about the Foundation, including past grants, participation in Foundation-sponsored events, and/or discussions with staff about the project idea.

Dr. Tamar Stein is an investigator seeking to devote her research career to answering life’s biggest questions. This is Dr. Stein first application with the foundation, and she was extremely excited to learn about the foundation and its cause, which are aligned with her research. As such, she will be very happy to take part in foundation events, to communicate her science both to other scientists and to non-scientific crowds, and to contribute to the foundation cause as much as she can.

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Bera, P. P., Stein, T., Head-Gordon, M., & Lee, T. J. 2017, Astrobiology, 17, 771

Candian, A., Zhen, J. F., & Tielens, A. G. G. M. 2018, Phys Today, 71, 38

Kronik, L., Stein, T., Refaely-Abramson, S., & Baer, R. 2012, Journal of Chemical Theory and Computation, 8, 1515