

Low Temperature Synthesis of Three Cyanocyclopentadiene Isomers and their Role in Interstellar Cyano PAH Formation

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The present manuscript by D. González et al. entitled Low-Temperature Synthesis of Three Cyanocyclopentadiene 1 Isomers and their Role in Cyano-PAH Formation in the 2 Interstellar Medium reports low-temperature experimental reactions between cyano radicals and 1,3-cyclopentadiene, leading to the formation of cyanopentadiene isomers. The topic is highly relevant, not only from the perspective of chemical reaction dynamics but also for astrochemistry, where the growth of molecular complexity remains poorly understood and largely unexplained.

Despite the topical nature and potential relevance of the study, the results do not appear to provide a breakthrough that significantly advances understanding in this area. While the authors describe several possible reaction pathways using high-level theoretical calculations, identifying multiple transition states that may lead to isomerization and different products, the final theoretical outcomes are not fully consistent with the experimental observations. As a consequence, key questions remain unresolved, particularly regarding the formation of the 5-cyanopentadiene isomer.

Overall, in my opinion, the present study does not reach the level of novelty and impact required for publication in the Nature Communications journal

Minor comments and points requiring clarification or revision in a future submission:

- Figures 1 and 2 are presented in the Introduction, but the corresponding molecules are not discussed in the text. These structures are already described in the cited references; their inclusion here should be justified or reconsidered.
- When the authors state: "The reactive scattering signal was recorded at mass-to-charge (m/z) ratio $m/z = 91$ ($C_6H_5N^+$), suggesting the formation of a molecule with the formula C_6H_5N plus atomic hydrogen (reaction (1))", it is unclear whether the hydrogen refers to a neutral H radical or to H^+ .
- What is the mass resolution of the experiment? With the reported resolution, can $m/z = 90$ and 91 be unambiguously distinguished?
- In Figure 4b (lower panel, high angle), the mass scan shows a clear shoulder that is not discussed. Which fragment could be assigned to this feature?
- Figure 5 is described and discussed in terms of "chemical pathways," but it does not represent a potential energy surface. Rather, it is an energy diagram, and the terminology should be corrected.
- Supporting Information: A clearer laboratory schematic should be provided. In its current form, it is difficult to identify the location of the distillation head and condenser.

Reviewer #2

(Remarks to the Author)

The manuscript presents a combined crossed molecular beams and electronic structure study of the reaction between the cyano radical and 1,3-cyclopentadiene under single-collision conditions. The authors demonstrate that this barrierless, exoergic reaction produces three isomeric cyanocyclopentadienes: 1-cyanocyclopentadiene (p1), 2-cyanocyclopentadiene (p2), and the previously astronomically undetected 5-cyanocyclopentadiene (p3). RRKM calculations predict that p3 is the dominant product. This is an excellent, well-executed study that combines state-of-the-art experimental techniques with high-level theoretical calculations. The findings are significant for understanding the formation pathways of cyano-substituted aromatics in the interstellar medium (ISM) and for guiding future observations. The manuscript is clearly written, the figures are informative, and the data well support the conclusions. I recommend publication in Nature Communications

after addressing the point below.

Relevance to low-temperature ISM conditions: The experiments were performed at a collision energy of 17.9 kJ/mol, which is much higher (translational temperature) than the 10 K environment of TMC-1. The authors argue that the reaction is barrierless and therefore accessible at low temperatures, and they present RRKM branching ratios extrapolated to 0 kJ mol⁻¹. The RRKM calculations assume statistical behavior and rely on the computed potential energy surface. The authors should provide more commentary on potential non-statistical and dynamical effects.

Reviewer #3

(Remarks to the Author)

Dear Editor, Dear Authors,

the manuscript by Gonzalez et al. describes a formation pathways and low-temperature synthesis of X-cyanocyclopentadiene (3 different isomers). The molecule in question and information about its creation pathway is certainly of high interest for the astrophysical community.

The manuscript is well written, figures are legible and the color coding is clear, although:

1. probably a better 3 colour "scheme" should be used to distinguish the different pathways in Fig.5.;
2. the color coding for atoms in Fig3. should also be applied in Fig 6.

The paper combines the experiment (crossed molecular beam) and electronic structure calculation (DFT, somewhere refined to CCSD(T)) and RRKM for branching ratios calculations. Details are described sufficiently in an elaborate SI.

The problems:

1.) The title of the paper starts with "Low-Temperature..." and then on l. 143 one learns, that: collision energy is ~18 kJ/mol. This doesn't look "Low-Temperature" in combination with astro/ ISM and especially: cold molecular clouds (in conclusion).

Moreover, I haven't found any discussion of this anywhere in the article. I feel it should be at minimum discussed/ reasoned.

2.) On one hand, it's true, that the studied reaction is quite exothermic, on the other hand there is no direct pathway to any of the 3 cyano-CPD, that does not involve "negative" barriers (i.e. barriers that are only relative to the intermediary species).
In general, it's expected that the computational results are going to be affected by the selected methods DFT vs. ab initio, methods parameters etc., which is fine, but problematic for next point:

3.) The experiment can not reveal what isomers has been observed.

With combination of only a calculation revealing the isomer structure and the last 'negative' barriers before the products being only ~7 kJ/mol apart (-65, -72, -79, fig 5.), which is WITHIN THE 20 kJ/mol initial collision energy,

I beleive that such a strong claim:

"" 67% low-temperature production of the isomer that has not been observed in space ""
is not justified enough.

4.) l. 313. "" By revealing that the primary formation pathway leads to a currently unobserved species, our study highlights the indispensable role of laboratory benchmarks... ""

In connection with point 3.) => There is nothing from laboratory experiments that supports this claim/ it's purely computationally justified.

Again, at absolute minimum, this would have to be changed to reflect that it's only the computation, with \Deltas between the barriers lower than the initial kinetic energy, what 'supports' this claim in this manuscript.

Even better would be an isomer sensitive experiment (which is probably out of scope of this work).
In that case, the writing must be absolutely clear, that the isomer results are purely computational.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

The authors have adequately addressed all the issues and comments raised. The manuscript is now acceptable for publication.

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Reviewer 1

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Minor comments and points requiring clarification or revision in a future submission:

1. Figures 1 and 2 are presented in the Introduction, but the corresponding molecules are not discussed in the text. These structures are already described in the cited references; their inclusion here should be justified or reconsidered.

Response: Figures 1 and 2 were included in the Introduction to provide a clear visual reference for the molecular structures mentioned in the text. While these species are indeed described in the cited literature, we felt that presenting their structures upfront would improve readability and help orient the reader. We have revised the text and added the following sentence for Figure 1:

“These molecular structures are shown in Figure 1 to provide a visual overview of representative species relevant to the present astrochemical context”

And for Figure 2:

“...whose structures are displayed in Figure 2, to illustrate their chemical complexity.”

2. When the authors state: “The reactive scattering signal was recorded at mass-to-charge (m/z) ratio $m/z = 91$ ($C_6H_5N^+$), suggesting the formation of a molecule with the formula C_6H_5N plus atomic hydrogen (reaction (1))”, it is unclear whether the hydrogen refers to a neutral H radical or to H^+ .

Response: We thank the reviewer for this clarification. However, in the cited sentence, the reference to reaction (1) explicitly denotes the formation of a neutral hydrogen atom (H) as the co-product. Thus, the hydrogen referred to is a neutral H rather than H^+ . To avoid any ambiguity, we have modified the text to explicitly state “neutral hydrogen atom (H)”.

3. What is the mass resolution of the experiment? With the reported resolution, can $m/z = 90$ and 91 be unambiguously distinguished?

Response: The quadrupole mass spectrometer used in our cross beams experiment operates with unit mass resolution ($\Delta m \approx 1$ amu), which allows adjacent mass-to-charge ratios such as $m/z = 90$ and 91 to be clearly distinguished. Under our experimental conditions, signals at neighboring integer m/z

values are well separated without significant overlap. Therefore, consistent with this resolution, no measurable signal was detected at $m/z = 90$, whereas a distinct signal was observed at $m/z = 91$. This confirms that the contribution at $m/z = 91$ cannot be attributed to spillover or insufficient mass discrimination from $m/z = 90$.

4. In Figure 4b (lower panel, high angle), the mass scan shows a clear shoulder that is not discussed. Which fragment could be assigned to this feature?

Response: We thank the reviewer for pointing out this feature. The weak shoulder observed in the high angle of the lower panel in Figure 4b most likely arises from minor fragmentation following electron-impact ionization in the detector and/or from a small contribution of dissociative ionization of the $C_6H_5N^+$ species. Because of its low intensity and the absence of a distinct TOF pattern or angular dependence, we cannot assign this feature unambiguously to a specific fragment.

5. Figure 5 is described and discussed in terms of “chemical pathways,” but it does not represent a potential energy surface. Rather, it is an energy diagram, and the terminology should be corrected.

Response: Accordingly, we have revised the figure caption and the corresponding discussion in the manuscript to describe Figure 5 as a reaction energy diagram and have adjusted the associated terminology throughout the text.

6. Supporting Information: A clearer laboratory schematic should be provided. In its current form, it is difficult to identify the location of the distillation head and condenser.

Response: We thank the reviewer for this suggestion. We have changed the Figure S1 of the Supporting Information by providing an improved laboratory schematic with clearer labeling and identification of the distillation head and condenser.

Reviewer 2

The manuscript presents a combined crossed molecular beams and electronic structure study of the reaction between the cyano radical and 1,3-cyclopentadiene under single-collision conditions. The authors demonstrate that this barrierless, exoergic reaction produces three isomeric cyanocyclopentadienes: 1-cyanocyclopentadiene (p1), 2-cyanocyclopentadiene (p2), and the previously astronomically undetected 5-cyanocyclopentadiene (p3). RRKM calculations predict that p3 is the dominant product. This is an excellent, well-executed study that combines state-of-the-art experimental techniques with high-level theoretical calculations. The findings are significant for understanding the formation pathways of cyano-substituted aromatics in the interstellar medium (ISM) and for guiding future observations. The manuscript is clearly written, the figures are informative, and the data well support the conclusions. I recommend publication in Nature Communications after addressing the point below.

Relevance to low-temperature ISM conditions: The experiments were performed at a collision energy of 17.9 kJ/mol, which is much higher (translational temperature) than the 10 K environment of TMC-1. The authors argue that the reaction is barrierless and therefore accessible at low temperatures, and they present RRKM branching ratios extrapolated to 0 kJ mol⁻¹. The RRKM calculations assume statistical behavior and rely on the computed potential energy surface. The authors should provide more commentary on potential non-statistical and dynamical effects.

Response: We thank the reviewer for raising this important point regarding the applicability of RRKM theory under the low-temperature conditions relevant to TMC-1 and the possibility of non-statistical effects. To address this, we have extended the manuscript by including *ab initio* molecular dynamics simulations on the computed potential energy surface. These simulations allow us to explicitly assess the role of dynamical effects and evaluate the validity of the statistical assumption across the relevant energy range, by calculating the relative populations of the **i1-i4** intermediates. The following text has been added accordingly in the manuscript:

“Molecular Dynamics Simulations: Rate constants theories such as RRKM predict product branching ratios of unimolecular reactions. It assumes that the lifetime of the reaction intermediates is much longer than the intramolecular energy redistribution (IVR), as well as that the reaction strictly follows the intrinsic reaction coordinate (IRC), i.e., no direct reactions in which products formed immediately after the bimolecular collision without an intermediate. To use RRKM theory to predict the product branching ratio of the titled reaction, the populations of the collision induced intermediates, e.g., i1, i2, i3, and i4 in Figure 5, are required. These populations cannot be derived from the potential energy profiles alone, as they depend on the access energy and entrance channel. In the absence of direction reactions, immediately after the collision induced intermediates are formed, the excess energies are largely localized in newly formed bonds, which is then deposited to the entire molecule through IVR. Therefore, *ab initio* molecular dynamics (AIMD) simulations were performed to determine the population of these intermediates and whether direct reaction makes up a significant portion. These

simulations were carried out long enough - longer than IVR - until the population of the intermediate becomes stable, after which their decomposition can be assumed to be statistical and hence follows RRKM. It is important to note that while AIMD simulations could be in theory extended until products eventually formed, under the condition of the titled reaction, the collision induced intermediates do not dissociate to products within a practical AIMD simulation time frame. Across all 280 bimolecular collision AIMD trajectories, 124 formed an intermediate and there was no direct reaction. No hydrogen atom loss products were observed up to 3 ps and an overwhelming majority of the trajectories remains as the collision induced intermediates (Figure S3). This is in line with experimental findings revealing long lived reaction intermediates. The AIMD simulations show that association of the reactants occurs predominantly through intermediate i1, with smaller contributions from i3 and i2, while formation of i4 is comparatively rare and no trajectories were observed to associate through i5 (Table 2). The only observed isomerization was between i1 and i2 through i5, although they are statistically insignificant (3 out of 124 trajectories). This “trapping” phenomena is common in other bimolecular collision systems that form stable intermediates.⁴¹⁻⁴³ These dynamics-guided intermediate population has been used to predict product branching ratios with RRKM theme reported. As Table 2 shows, since AIMD simulations show no direct reactions, the dynamics-guided, RRKM branching ratio of p1 (29 %), p2 (4 %) and p3 (67 %) aligns well with the intermediate-independent RRKM branching ratio (Table S10).

Table 2: AIMD-derived association ratios of the low-energy intermediates.

Intermediate	Relative population (%)
i1	63.89
i2	12.27
i3	17.87
i4	5.98
i5	0

- 41 Goettl, S. J. *et al.* Correction: Gas-phase synthesis of the bicyclic silicon tricarbid molecule (c-SiC₃) as a precursor to silicon carbide nanoparticles in space. *Chem. Sci.* **17**, 5759-5759 (2026).
- 42 Yang, Z. *et al.* Directed Gas-Phase Formation of Azulene (C₁₀H₈): Unraveling the Bottom-Up Chemistry of Saddle-Shaped Aromatics. *ACS Central Science* **11**, 322-330 (2025).
- 43 He, C. *et al.* Directed gas phase preparation of ethynylallene (H₂CCCHCCH; X¹A') via the crossed molecular beam reaction of the methylidyne radical (CH; X²Π) with vinylacetylene (H₂CCHCCH; X¹A'). *Phys. Chem. Chem. Phys.* **24**, 26499-26510 (2022).

Reviewer 3

Dear Editor, Dear Authors, the manuscript by Gonzalez et al. describes a formation pathways and low-temperature synthesis of X-cyanocyclopentadiene (3 different isomers). The molecule in question and information about its creation pathway is certainly of high interest for the astrophysical community. The manuscript is well written, figures are legible and the color coding is clear, although:

1. probably a better 3 colour "scheme" should be used to distinguish the different pathways in Fig.5.

Response: We have revised the color scheme in Figure 5 to improve the distinction between the three pathways and enhance the overall clarity of the figure. We hope that the updated representation improves readability and facilitates interpretation.

2. the color coding for atoms in Fig3. should also be applied in Fig 6.

Response: The same color coding for atoms used in Fig. 3 was already applied in Fig. 6. However, it may have not been sufficiently clear in the original version. To improve clarity, both Fig. 3 and Fig. 6 have been added with better resolution to the manuscript.

The paper combines the experiment (crossed molecular beam) and electronic structure calculation (DFT, somewhere refined to CCSD(T)) and RRKM for branching ratios calculations. Details are described sufficiently in an elaborate SI. The problems:

1. The title of the paper starts with "Low-Temperature..." and then on l. 143 one learns, that: collision energy is ~18 kJ/mol. This doesn't look "Low-Temperature" in combination with astro/ ISM and especially: cold molecular clouds (in conclusion). Moreover, I haven't found any discussion of this anywhere in the article. I feel it should be at minimum discussed/ reasoned.

Response: We thank the reviewer for this comment. Although the crossed molecular beam experiments were conducted at a collision energy of ~18 kJ mol⁻¹, the underlying reaction mechanism is barrierless and exoergic, with all transition states and intermediates lying below the energy of the separated reactants. Consequently, this reaction is expected to proceed efficiently even under the low-temperature conditions prevalent in the cold molecular clouds of the interstellar medium. We have addressed this point throughout the paper and clarified this aspect in the revised text.

2. On one hand, it's true, that the studied reaction is quite exothermic, on the other hand there is no direct pathway to any of the 3 cyano-CPD, that does not involve "negative" barriers (i.e. barriers that are only relative to the intermediary species). In general, it's expected that the computational results are going to be affected by the selected methods DFT vs. ab initio, methods parameters etc., which is fine, but problematic for next point: The experiment cannot reveal what isomers has been observed. With combination of only a calculation revealing the isomer structure and the last 'negative' barriers before the products being only ~7 kJ/mol apart (-65, -72, -79, fig 5.), which is WITHIN THE 20 kJ/mol initial collision energy, I beleive that such a strong claim: "" 67% low-temperature production of the isomer that has not been observed in space"" is not justified enough.

Response: We thank the reviewer for this thoughtful and important comment. Crossed molecular beam experiments alone cannot unambiguously distinguish between the individual cyanocyclopentadiene isomers and, therefore, the product branching ratios rely on the underlying electronic structure calculations and RRKM analysis. We also acknowledge that the relative energetics and predicted branching fractions may depend on the level of theory employed.

However, the computational results consistently indicate that the reaction proceeds through barrierless pathways leading to multiple cyanocyclopentadiene isomers, with the associated exit barriers located below the energy of the separated reactants. While the relative differences between the exit transition states are indeed smaller than the experimental collision energy, the calculated product distribution is governed not only by the barrier heights but also by the density of states and statistical partitioning of the energized intermediates.

To address the reviewer's concern, we have modified the wording throughout the manuscript and now refer to the predicted branching ratios as computationally derived.

4. 1. 313. "" By revealing that the primary formation pathway leads to a currently unobserved species, our study highlights the indispensable role of laboratory benchmarks... "" In connection with point 3.) => There is nothing from laboratory experiments that supports this claim/ it's purely computationally justified. Again, at absolute minimum, this would have to be changed to reflect that it's only the computation, with Δ s between the barriers lower than the initial kinetic energy, what 'supports' this claim in this manuscript. Even better would be an isomer sensitive experiment (which is probably out of scope of this work). In that case, the writing must be absolutely clear, that the isomer results are purely computational.

Response: As stated above, we have revised the manuscript to explicitly distinguish between the experimental findings and the computational results. Specifically, we have softened statements implying experimental confirmation of a dominant isomer and now clarify that the predicted formation of the currently unobserved cyanocyclopentadiene isomer is based on the theoretical results. We agree that an isomer-selective experiment would provide a more definitive validation, although such measurements are beyond the scope of the present work.

We hope that the revised version is acceptable for publication.

Thank you

Ralf

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