Experiments on Cold Molecules Produced via Stark Deceleration

by

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Jun Ye

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Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Experiments on Cold Molecules Produced via Stark Deceleration

Thesis directed by Prof. Jun Ye

The work described in this thesis is the construction and operation of a Stark deceleration apparatus. Specifically, this work represents only the second successful implementation of the method[1] and the first deceleration of the hydroxyl radical (OH) and the formaldehyde molecule (H_2CO). Experimentally, much of the work in the beginning of our experiments was the construction of a suitable molecular beam. Though molecular beams have been used for decades in physical chemistry, the design goals of the typical physical chemistry experiment are very different than ours, and as such, much work was required to adapt these sources for Stark deceleration. Since the maximum-attainable, decelerated molecular density is set at this stage, the importance of a good molecular beam source cannot be understated. Once a stable decelerated beam became routine in our laboratory, we performed the first precision measurement on cold molecules leading to the best ever values for the frequencies of the main lines in the lowest OH Λ-doublet. These measurements, when coupled with the appropriate astrophysical measurements, can be used to put the most stringent constraints on the variations of the fundamental constants. Excitingly, we have recently been informed that the required astrophysical measurements may be performed as early as the latter part of this year.

Our most recent work, not covered in this thesis,[2] has been the construction and implementation of a magnetic trap for OH molecules. To prepare decelerated molecules for loading into this trap we have built a second-generation decelerator, which has more stages than our first, to provide a higher flux of decelerated molecules. In the construction of this decelerator, several interesting phenomena, which currently limit

[1] The Berlin group, whose collaboration has been fruitful (for both sides, I hope), was first.
[2] This topic will likely be the crux of the dissertation of Brian Sawyer.

the decelerator efficiency, have come to our attention. Specifically, these are transverse over-focussing of the decelerated molecular packets in the decelerator and the possibility of Majorana type transitions during deceleration. These effects (especially transverse over-focussing) extremely limit the number of molecules decelerated to below 15 m/s in our apparatuses. Since molecules of this speed or less are required for proper loading into our magnetic trap, both of these phenomena **must** be addressed in order for the optimal deceleration performance to be reached. Currently, as detailed in this thesis, experiments are already underway to learn how to eliminate them. Thus, it is my opinion that the technique of Stark deceleration is very close to blossoming into the best technique for producing cold molecules,[3] since addressing these issues will lead to several orders of magnitude gain in decelerated molecule number. Furthermore, with ideas for further cooling of trapped samples being developed, *e.g.* cavity-assisted Doppler cooling, the possibilities for cold molecule physics are staggering.

[3] Perhaps this argument could already be made.

Dedication

For Natasha

Acknowledgements

As anyone who has worked in a research environment will tell you, success requires a large number of great people working together. I have been fortunate enough to work at JILA in Prof. Jun Ye's group, which can be defined as a 'large number of great people working together'. In some sense, I feel I was in an environment where it was impossible to fail because the people around me would not allow it to happen, and as such, I am indebted to many. The help I received from the JILA electronics shop (Terry Brown, Mike Whitmore, James Fung-a-Fat, Paul Beckingham, Carl Sauer, and David Tegart) was instrumental in both the production and detection of our cold molecules. Likewise, without the aid of the JILA instrument shop (Alan Pattee, Hans Green, Kim Hagen, Tom Foote, Tracey Keep, and Blaine Horner), our decelerator would never have been constructed. These individuals are more than engineers and excellent technicians, they are artisans who have mastered their craft. In the laboratory I have had the pleasure of working with many great scientists. I still remember my first visit to the lab (to see the empty table) when I met Jason Bochinski, the project's first postdoc. Together, Jason and I navigated the perils of switching high voltages and making a molecular beam, and though Jason was clearly the leader, he never belittled my contributions and for that I am grateful. Almost two years later Heather Lewandowski joined the effort as a postdoc, and it was from a series of fruitful discussions with her that the work that comprises Chapter 6 sprung forth. Brian Sawyer was next on the scene as the graduate student who would take over my position. I have thoroughly enjoyed every moment I have worked with Brian, especially the construction of our second decelerator. His relaxed attitude and sharp mind have greatly accelerated the progress of the project. At the beginning of the year Benjamin Lev started working with us as a postdoc. Benjamin quickly took over the high resolution spectroscopy experiment, and I am completely impressed with his wit and attention to detail. Last to join our group was Ben Stuhl, a graduate student. While Ben and I have only worked together for a few short weeks, he has already taught me much about coding, and I expect only the best things from him in the future. Outside of the cold molecule laboratory I have had the benefit of a close relationship with the theory group of John Bohn. John, his posdocs, and his students (Alexander Avdeenkov, Chris Ticknor, and Ed Meyer) have taught me molecular physics. I have also been fortunate to have a close relationship with the group of Gerard Meijer in Berlin. The friendly competition/collaboration with this group, the originators of the Stark deceleration technique, has not only accelerated the development of the field, but has left me with many wonderful friends (Rick Bethlem, Floris Crompvoets, Bas van der Meeraker, Joop Gilijamse, Steven Hoekstra, Nicolas Vanhaecke, Joost Bakker, Jacqueline van Vandhoven, and Gerard Meijer). Of course, none of this work would be possible without the guidance of Prof. Jun Ye. It is impossible to overstate the importance of Jun to the success of the experiment. In the difficult times Jun always seems to know the right way to proceed. Furthermore, working for Jun is a joy because he is as committed to the growth of his students as he is to doing excellent science. Jun has allowed me to travel around the globe to further my development as a scientist, and I cannot begin to explain how important those trips have been to me. If I ever have my own laboratory, I can only hope to approach the excellent leadership Jun has demonstrated.

Beyond the amazing people at JILA and in Jun's group, there is another element to how easy it is to succeed here. This element, which is somewhere between an ideal and an attitude, – maybe Zeitgeist is the right word – is a sense of family that pervades the institution. Whether it is loaning equipment or taking the time to talk with someone about a problem on their experiment, this approach greatly decreases the time it takes for good science to be done. More importantly though, it makes for a non-stressful work environment. I am not sure how this culture comes to prevail at an institution. Perhaps the foundation was laid by the early Fellows, or it has to do with living in such a beautiful place as Boulder, *e.g.* even if the laser breaks, you can still go skiing on the weekend. Regardless, it is, in my opinion, the gold standard for any working environment and I hope to help recreate wherever I work.

I am extremely indebted to my parents, Raymond and Christine. Though they knew the importance of education, they never pushed me into anything, preferring to let me find my own way. I credit this relaxed atmosphere as the reason I was able to make it this far. Because I enjoyed what I was doing, I was never 'bogged-down' by the work. Nonetheless, the most important gift I received from my parents was a strong faith in Christ. In retrospect, it was my beliefs as a Christian that led me to physics. In my opinion, there are scarce better ways to know God than to study his creation, and the beauty and symmetry I have found in physics have only strengthened my faith. And any reader who thinks that things like religion or prayer have no place in a laboratory has never applied 30 kV across a couple of millimeters.

I certainly owe the most, however, to the person this work is dedicated, my wife, Natasha. I cannot even begin to describe (or understand) all the ways she has helped me. She is somehow able to be both an encourager and a truthful critic at the same time, and it is her honest love that keeps me grounded squarely in reality. Of all people, she has also sacrificed the most for me. She has patiently allowed me to work the long hours required, and has always been there for me at the end of the day. I am not sure that I can ever repay her, but I am looking forward to a lifetime of trying.

Contents

Tables

Table

Figures

Figure