



Perspectives on Research

jur interviews Todd Krauss, Ph.D.

Todd Krauss is an Associate Professor of Chemistry at the University of Rochester.

jur: So first could you tell us a little about your educational and professional background?

Krauss: I've been a New Yorker all my life; I grew up on Long Island and studied at Cornell University, where I majored in applied and engineering physics (AEP), which is not a common program. Basically it's an engineering degree but with significant physics training. So my first few years consisted of core engineering courses: mechanical, civil, electrical, materials, etc. Towards junior year in the program you begin to specialize in AEP, in this case by taking mostly physics courses but with an added emphasis on applications. Topics like fluid dynamics and condensed matter physics were the more popular courses, more so than courses like string theory or astrophysics (which aren't necessarily going to lead to practical applications here on Earth). The nice thing about the program was its size: there were only fourteen faculty members or so, so it had a "small" feel like here at UR but with this huge university to draw from. For various reasons I ended up staying at Cornell for graduate school, so I received my masters and my Ph.D. there as well. These were in the same department, but for graduate students it is just referred to as applied physics. After receiving my Ph.D. in 1998, I went to Columbia University for two years to study chemistry with Louis Brus, a well-known figure in nanotechnology. I was there until 2000, which was when I came here. I was an Assistant Professor until 2006 when I was promoted to Associate Professor.

jur: When did you first participate in scientific research, and what kind of research were you involved in as an undergraduate and as a graduate student?

Krauss: As an undergraduate I didn't do much research because I was in the Army ROTC program, which took a lot of my time, particularly during the summer; it was nearly impossible to get involved in research. As a senior I started to work in the lab of John Silcox, who is very well-respected and one of the most senior members of the faculty down there. He works in the field of scanning transmission electron microscopy. I was

building the vacuum apparatus for a new electron microscope instrument. I soon decided that I wanted to go to graduate school and eventually get a job like the one I have now. For graduate school I didn't necessarily want to work in pure material physics; I wanted to somehow work with photons, with light. Lasers fascinated me. However, I didn't want to just build lasers as a Ph.D. student, but I certainly wanted to do something with light, to use optical phenomena for something. So when I was looking for research advisers as a senior, I came across Frank Wise, who was teaching the junior level quantum mechanics course. I always liked quantum mechanics and I did well in it, and I thought it was interesting how at certain length scales, when you look closer and closer, strange phenomena start to happen. Wise had just started to study these nanoparticles, which are minuscule chunks of semiconductor made of lead and sulfide. Large pieces of lead sulfide are used in infrared detectors. But when you make lead sulfide very small, strange quantum mechanical things begin to happen. I thought it would be great if we could work on these particles; since Frank Wise was a laser person, we could use some of the laser training I was getting and start to examine the particles with lasers - that was my very naive thinking at the time. So that's how I really started to get into research. I spent a lot of time in graduate school actually not working on my thesis. It is really common for graduate students to hunt around looking for something interesting before specializing and putting together a thesis. I had a lot of experience with some microscopy, but more with ultrafast optical spectroscopy.

jur: What are your current research interests, and how did you get interested and involved in that specific field?

Krauss: My research group is interested in a lot of diverse things, which could be considered atypical, especially for a somewhat younger person like myself. I have always had this fascination with nanoparticles and their fundamental properties. That's what excites me, the new discoveries we might come across. I suppose it's like Star Trek, the new frontier: you don't know what you're going to get in different episodes, but you know it will be something new and different. We start looking for physical phenomena, with some predictions as to where to go, and we follow that. My research interests (as for any faculty

member, especially younger ones) are really a mixture of what I did as a graduate student and as a postdoctoral fellow, and what I've come up with on my own. Some things are even vestiges of what I did as an undergraduate student; we still have an ultra-fast laser in the lab where we excite particles and look at electrons in an excited state, to see where that electron goes energetically and how it relaxes back to where it was, and how fast it does that. That tells us a lot about how these particles "tick" internally. Then as a postdoctoral fellow I really got into materials called carbon nanotubes. They are all carbon; but diamond is all carbon, and graphite is all carbon, and a lump of coal is all carbon. A carbon nanotube is a very different material, like a little cigar tube of carbon, a nanometer across, but potentially microns or millimeters long. But they are single molecules - normally chemists only work with molecules that are small on all dimensions: water, or nicotine, or whatever an organic chemist can cook up. Those are small things; even all the drugs organic chemists create for the health care industry and stuff like that are small in every dimension. Carbon nanotubes are small in two dimensions, but they can extend forever in the third dimension, so with nanotubes we can really start to connect molecules to the outside world. We are studying these nanotubes on a number of levels. One of the ways we study them is with ultra-fast laser spectroscopy, which we already talked about. Another thing we do is look at them one at a time, which is quite painful; we essentially spread them out completely far apart on a piece of glass and move a molecule to our laser beam to look, for example, at their fluorescent properties, one at a time. That's something we've sort of picked up largely from my postdoctoral studies and carried forward.

Since I've been here we've had new projects, things I never thought I would be doing. Part of my group works on biological sensing using DNA based sensors, and I have started a little company with Professor Ben Miller in Dermatology for them which will start pursuing that idea into engineering and creating a device. We also recently received a grant (with Professor Kara Bren in Chemistry) to do work with single protein folding. Folded proteins cause things like Alzheimer's, Parkinson's, mad cow disease, cancer, and other major diseases. People have looked at them for fifty years, and nobody understands why proteins just fold the way they do. Folding randomly, it would take the protein something like ten billion years to fold itself correctly; it somehow has to "know" intrinsically how to fold, and we're trying to understand that. So that's a new direction in which we've been moving. And then another new direction is energy. The more I've gotten into different areas of science, the more I've realized that we're in some serious trouble when it comes to energy and energy policy and things like that. It's not because I think the world's going to run out of oil anytime soon; it's more that we're doing a massive experiment on a global scale in terms of carbon dioxide atmospheric production. By the time today's undergraduates are fifty or sixty, at our current pace we're going to double the carbon dioxide in the atmosphere. And no one knows how that's going to affect things. One effect will be global warming, but that's not really the critical issue; the critical issue is what happens to life when we have all this carbon dioxide, and global warming could just be one side effect in the end. The last time this experiment happened was around 220 million years ago or so, and ninety percent of the

planet died, so we're really rolling the dice here. I think it's important that we find alternative energy sources sooner than later, so we're starting to do some work in that area as well. Protein folding and sustainable energy are two grand challenges for the group coming up over the next twenty years.

jur: What exactly are nanometer-scale materials and devices, and how do they contribute to the creation of photonic devices and biological sensors?

Krauss: A good fraction of our research is very fundamental. We're trying to understand the behavior of semiconductors at a nanometer scale. Cadmium selenide is an example of a material we study, though it isn't used for too much in its bulk form; lead selenide is another example; in its bulk form is used all over the place in infrared detectors. Silicon is another good example of a very useful semiconductor material, though we don't study it in our lab; for instance, there's a little piece of silicon in every iPod powering it, giving it all the instructions - on it are transistors and wires and everything that allow your iPod or my computer to work. The reason why the iPod is fairly thin is because we've taken what used to be computer technology that would fill this room and shrunk it down to the size of an iPod or smaller. What makes this whole process possible is that as you shrink the silicon, as you make it smaller and smaller, there are no differences in the properties - it behaves as a giant piece of silicon. However, when you reduce something to the size of around five nanometers, you start to see strange things happening. One example is shown on my website - a picture depicting solutions displaying a rainbow of colors. In each solution is the same material, cadmium selenide, but with the size of the particle changed by a factor of 2 from left to right - we get it to glow from blue (an energy state with 2 units of energy) to red (1 unit of energy, changing the energy substantially). If you were to do that with a piece of silicon, you would have to actually utilize other materials; and some of that is in fact done - they put in some phosphorous or some arsenic, and that would change the energy states somewhat. But by the time you got done with doping the silicon, it would not be silicon any more - you would have changed things too drastically. So the change in color (i.e. energy) with size is the basic fundamental effect.

The question is, what else is out there that we don't understand? When we make materials that have some interior atoms but some surface atoms, what are their properties? Our particular research area is looking at the fluorescence and optical properties of these nanoparticles, and I would include our work in the carbon nanotubes in that area as well. A nanotube is a rolled-up single sheet of graphene; graphene itself is a metal - conductive, though not a very good metal. But if you roll it up into a tube, you can actually get metallic or semiconductor behavior based just on how you roll it. Chemists haven't figured out how to make these yet with any sort of reliability, but if you could make a semiconductor one and connect it to a metal one on each side, you would have a transistor that is just a nanometer across. This would have significant applications (for instance, shrinking the iPod down to something much smaller, in principle). So there is a lot of potential out there, but before we can get into any of that, we've got to understand how these nanometer scale things

work. Here's a good example of fundamental work leading to getting some new technological devices. For years and years people studied the relaxation of quantum dot excited states electronically. You would excite an electron into a higher energy state to see where it would go in energy and how fast it took to get there. What was found was that if you put two electrons in higher energy states, one electron essentially killed the other one, and all of a sudden you had only one electron there. If you're trying to get these quantum dots to emit light, if you put two photons in, what you want is two photons out; that's the most efficient process, though you never quite get that. But what was found was that you would only get one out at best, which was killing the luminescence, and if you can't get a particle to luminesce, you can't get a laser, which is just an amplification of that luminescence. So before we understood how to make quantum dot lasers, we needed to understand the fundamental properties. Once we understood them, we could make a better laser and try to get around this electron-electron annihilation process. So the devices are coming, based on leveraging some of the fundamental science that we do first.

We're also doing some device work directly. In collaboration with Michal Lipson, Professor in Electrical and Computer Engineering from Cornell, we're trying to make a light move on a silicon chip. To couple light into silicon is very difficult; silicon itself isn't a very good optical material – it doesn't emit the right wavelengths. So why do this? For example, if you wanted to make faster phone calls or make the internet faster, what is limiting the potential speed is the electronics, the fact that you need electrons to move to transmit the signal. And if you could get rid of the electrons and make it transmit information using light, it would be a million times faster. However, to do that, you need light to move on silicon chips. And how do you do that? One way to do that is to put quantum dots on a piece of silicon, integrating it all together: quantum dots can be the luminescent material (to generate the light) and silicon can be the optoelectrical material that manipulates the light. So that's some of the work relating to devices that we've been doing. Also, for years and years, people at the medical school have used dye molecules for things like fluorescence-based imaging. For instance, if you want to look at for the presence of cancer cells, you can take a sample of cells and actually stain it with red fluorescent dye specific to the cancer cell to see if it glows red, and that can tell you whether the cells are cancerous or not. Quantum dots are much better than dyes in principle, because they are little but robust semiconductor materials. Organics, on the other hand, are pretty "wimpy" by comparison, just simple carbon bonds, while quantum dots are hard, inorganic "rocks," essentially; they can be brighter (than dyes), they don't bleach as quickly, you can have many colors... there are many advantages. We're just starting some of this type of research; we have several collaborations getting started with the medical school to try to use these particles in a biological environment. But the disadvantage is that they are inherently not biological, so some tricks are needed to get them into cells or attached to cells. We're trying to push them slowly in this area to see if we can get them to replace the dye molecules at some point, for then medical research overall would benefit from it. So, for example, we have projects with a group doing flow cytometry at the UR Medical Center trying to look at fluorescence based cell sorting and things like that,

trying to get these particles to be better for that application. We have a project with Günter Oberdörster in Environmental Medicine at the medical school looking at the toxicological effects of these particles on the body; you have to be careful if you want to use these particles for biological applications. Cadmium? Not good. Heavy metals? Not good. We want to know what's going to happen if we put these inside of people: Do the particles stay whole? Are they chewed up (i.e. do they disintegrate)? Does the cadmium leach out? And how do these particles in general affect the toxicological viability of cells? So that's another application of our work.

jur: Could you explain some of the techniques used in your research?

Krauss: Atomic force microscopy (AFM) is a technique that is essentially the nanometer-scale equivalent of a record player. The way a record player works is that there are bumps on the record that bounce the needle up and down, and these movements get translated into electrical signals that come out through the speakers as music. AFM works in the same way. Essentially there is a little needle on the end of a long diving board, and the needle goes up and down, as it hits a small nanoparticle or a nanotube. It actually moves only a nanometer or so high, but we take a laser beam and bounce it off the end of the "record player" needle and look at the reflection of the laser really far away; so even though the AFM tip is only moving a few nanometers up and down, far away we can get a signal. Then, if we split the detector that is measuring the laser power in half, we start to see the beam moving up and down, higher on one detector than on another, and we can use this to calibrate height. Now, in the end, the AFM tip needle does not care what is really hitting it. It experiences a force to move it, so if you can actually lift the tip off the surface and if there's charge on the needle tip, and you have a charge on your surface, they are going to interact through an electrostatic force. For instance, if you have two things that are positively charged, they will repel. So the laser in the end bends up and in the far field you see the change. So what we do is put a little charge on the needle AFM tip and then we go looking on the surface for charges on our particles. We actually have been able to modify a commercial instrument a little bit to be sensitive to a tenth of an electron's worth of charge at room temperature. So if there is an electron on the particle, it hops off, which we can see fairly easily. The big picture we are trying to understand is this: if we put electrons on these particles, what happens to their fluorescence? It's a solved problem for molecules: the molecule becomes "messed up" – in other words, the fluorescence is killed. It's a solved problem for macroscopic things like silicon: they don't care about extra charges. For nanoparticles this is a really important problem because if you want to do something like make a laser or a solar cell out of a nanoparticle, you don't want to have charges on the particles. You certainly want to know whether the fluorescence will be killed by additional charges, because that can really kill any potential application.

Another technique we use is single molecule spectroscopy. Ten years ago it was state of the art, but now we're getting it under fairly good control. Single molecule optical spectroscopy consists of a class of experiments where you look at molecules one at a time. The way we do it here is a brute force approach

where we look at single quantum dots, single nanotubes, or single proteins. You just find a way to spin them out, which is really neat. You just have a drop of liquid containing these particles and you just put it on a disk spinning at 5000 rpm or so, and the particles go everywhere. You end up with one particle per every couple of microns at best, sometimes even less than that. Then we can use the laser beam to look at fluorescence from the individual particles one at a time. So you can look at fluorescence and it turns out that your detectors, and even your eyes, are very sensitive and can see photons from single molecules as long as you excite them quickly enough; it's the background fluorescence that usually prevents this. So a lot of this type of experimental work is spent on reducing the background noise, and once you get that to below a certain level, the detectors see the single molecules easily. We can see all sorts of weird behavior when you look at one molecule. The fluorescence spectrum does many strange things, like moving around in wavelength or energy and going up and down in intensity. This is one of the reasons we look at single molecules, so we can understand what happens with this ensemble one at a time.

jur: What kind of applications could your research have?

Krauss: As I already mentioned, we've been doing some work that someday can be applied to improved solar cells. We're actually working with Kodak on a project in what is called all inorganic solid state lighting. Light bulbs, even fluorescent ones, are horribly inefficient. So much energy is wasted in heating the light bulb. It would be better if we could make light-emitting devices that are more efficient. So we are trying to make a device out of completely inorganic components, with the centerpiece being an emissive layer consisting of nanoparticles. We're working on that with Kodak's experts in emissive devices. I also mentioned protein folding and applications for that in terms of disease treatment. The "light on a chip" project is another one with technological relevance. With that project comes some laser work; what we want to do is put nanoparticles into special small optical cavities that will allow us to create really small-scale lasers for these applications involving light on a chip. A lot of our other work is more fundamental; applications would be something to look at later on down the road. We are not studying Alzheimer's disease, but understanding protein folding can solve that problem; on the other hand, we're not going to solve that problem ourselves. Our piece will contribute to solving this bigger problem. Hopefully someday we'll know how to tackle things like Alzheimer's or Parkinson's based on some offshoot of our research.

jur: In what ways do you interact with undergraduates?

Krauss: Many ways. I teach general chemistry; between myself and the other professor teaching the course, we get half the freshman class every year. I really enjoy that; it's a different interaction than what you would get dealing with a smaller class. I also teach a small laboratory class right now, and I have undergraduates working in my lab. So I have three levels of interaction. General chemistry is really fun and I really enjoy it. The students may not enjoy the material so much; chemistry is usually a required class and many people do not like to take

it, or would not take it if it was not required, but I hope by the end of the semester we at least have a good time. Of course, you can't get one-on-one attention for the most part; I try to encourage people to come to office hours, but you can't have two hundred students at office hours. On the other end of the spectrum, I have a smaller laboratory class, which is a lot more intimate, where I get to work with my students and teach them a lot about optical spectroscopy. This course is the most "uncanned" laboratory we have here at UR; half the time the equipment does not even work, and the students have to troubleshoot things. It's not actually intentional that things break down, it's that we're doing experiments that are essentially research-grade; it's not like simply putting something into a canned commercial instrument and making a measurement – everything is a homebuilt setup, and sometimes homebuilt things fail. There are three undergraduates in my laboratory with two active this semester. I interact with them several times a week on their research or even on other things; sometimes it's more along the lines of mentoring, with regards to applying to graduate school or advising where they should go. The undergraduates are certainly part of the lab and we treat them like graduate students; we understand that they have strong constraints on time, but when they are in the lab working they're simply part of the group.

jur: How can undergraduates get seriously involved in research in your field?

Krauss: My philosophy is that I don't like to give undergraduates busy work or "get the coffee" projects. I try to give them projects that give them the flavor of several things. One is what science research is like in general, so they are struggling for the most part, just like all of us, trying to get things to work, trying to understand their data, trying to push their science forward. I also try to give them a sense of what nanoparticles are like. Hopefully by attending group meetings and through their own research they get a feel not just for their own area but for the whole nanoscience field. I also give them a graduate student as a mentor/liaison, and they initially work on a subproject of one of the graduate students, generally something that the lab needs to get done or would like to get done, and on which they could use the assistance of a student, so that in the end of the day, if they are successful, they'll have some sort of publication. A good example would be James Camera, who graduated two years ago; he was working on a DNA sensing project. The larger project was taking DNA and putting it onto a piece of gold, and then coming in with complementary DNA, and it would bind to the DNA on the piece of gold, which would lead to a fluorescence response. We needed to know how much of that DNA was on the surface (how many molecules per square centimeter) and how it was arranged: was it all packed together, or spread out? So James looked into this and did some measurements, and he did a nice job with that; at the end of the day it became part of a paper, so James received an authorship out of it. That's the way undergraduates generally work in the lab. If you're creative, you can always find ways to get students involved in projects. I tend not to give them projects that are too technical or focused on building instruments, because then they would end up spending their senior years making instruments and not actually engaging in research. In my six



years here we've had several undergraduates involved in our research. One of them, Mike McCoy, is going to be a Take Five student this fall, and he is actually going to come back in the summer between his fourth year and his Take Five year to do additional research.

jur. Do you have any advice for undergraduates considering a research-oriented career, particularly in your field?

Krauss: It depends; there are many ways you can do research. When I was an undergraduate, I really thought that the faculty members were these lords of research and that they were echelons above everyone else in ability. As I developed as a graduate student I realized that while some were true titans of intellect, for the most part they were just smart people who had good common sense. To be a good researcher, of course you have to have some intellect, but a lot of it is just hard work and common sense. Quoting Einstein, genius is 99% perspiration and 1% inspiration. So if you can get the one percent out of it, the rest is just hard work.

The best advice I can give is to learn how to do things like change the brakes of your car. This may seem unrelated, but I've noticed that some of the students who are the best in research are the ones who are able to really get a feel for instrumentation and how experiments work. A lot of it is not easy to teach; it's very difficult to teach somebody how to know if the microscope is out of alignment or if the laser is out of alignment. If your brakes aren't working, you find out right away if you have technical ability when you smash into the next car. I was always interested in things like changing my brakes and changing my carburetor, getting mechanical things to work; and those are to some extent precursors to doing research. Get involved with a lot of things with your hands, other than just playing video games.

Another piece of advice that I have is not to specialize too early. As you get older you realize there is always so much you don't know, and what you don't know is always several orders of magnitude greater than what you do know. Many people take organic chemistry their sophomore year, decide they like it, and then decide to be a chemistry major and go into organic chemistry research; but they are missing this entire field, including inorganic chemistry, physical chemistry, materials chemistry, and biological chemistry. And that's just chemistry; there is also physics and engineering and all sorts of other options. So it's important to avoid tunnel vision. As an undergraduate, research is all free, at some level; but once you become a graduate student, you want to get out with a thesis in a reasonable time frame.

What helped me a lot was that I was able to do things with my hands, like soldering wires. Fixing your car if you own one or fixing your own bicycle can help. And in the process of fixing a derailleur on a bicycle and having the chain pop off every five minutes, you start to do similar processes to what you would do in an experiment. If my experiment is not working, I troubleshoot it. If my derailleur is not working, I troubleshoot that. If I move this screw or that screw, how does that affect things? So those are the kind of things that I think will enable you to be a successful researcher as you get older.

Finally, research is not always in academics. This is a great place to do research, and the wonderful thing about this job is

that within reason I can do pretty much whatever I want, as long as I can get it funded. But there is also research in companies and in government laboratories; there is research vicariously living as a program officer – through evaluating research you can be involved in it in some way. So there are many ways to be involved in research and science without teaching a general chemistry class a few days a week and having a few graduate students. I think that more top talented people need to get involved in my field and in science in general, and however people choose to do that is just fine.