A Conversation with Prof. Flemming Besenbacher: Innovator in Nanoscience and Nanoscience Education

I met with Prof. Flemming Besenbacher at his office in Aarhus, Denmark in August. We talked about the center he founded, iNANO, and his vision for nanoscience and nanoscience education.

PSW: What made you interested in nanoscience?

Flemming Besenbacher: I have been working in nanoscience for 25 years, doing scanning tunneling microscopy back in the 1980s.[1−7] I really got interested in nanoscience from an educational point of view.

I could see the way we were educating our students in Denmark; it was physics, chemistry, biology, and so forth. I had the dream to develop new bachelor's and master's curricula from scratch. We started in the fall of 2001 and launched the first bachelor's and master's programs. In September 2002, we took in our first new students. On January 28, 2002, we established the iNANO Center [the Interdisciplinary Nanoscience Center].[8] When I started to develop the curriculum, I was very keen to collect a critical mass of good colleagues—all of them working with different aspects of nanoscience—from physics, chemistry, and biology. They were also engaged as potential supervisors for bachelor's, master's, and Ph.D. students.

Figure 1. Flemming Besenbacher (left), Minister for Science, Technology and Innovation Helge Sander (center), and Cody Bünger (right) at the iNANO inauguration in 2002. Reprinted with permission. Copyright 2002 University of Aarhus.

It took off, and today we have three missions: education, research, and technology transfer.

But it was really the education aspect. I sent an application to the Danish Research Minister and Minister of Research and Education, because we had to have approval from them to establish it [Figure 1]. As far as I know, it was the first in the world. It was a lot of work. There was a lot of internal discussion, including resistance among physics and chemistry professors. I was increasingly unhappy about things, at least from the nanoscience point of view. Our physics education is great, but students are really taught atomic physics, molecular physics, astrophysics, nuclear physics, solid-state physics, and so forth. Our physics students had no bio courses whatsoever and very little chemistry! The same thing applied to molecular biology: there was a trend that they got courses in molecular biology but the basic training in physics, chemistry, and math was getting lower, and lower, and lower. So I thought we would put together curricula with the most important areas in physics, chemistry, bio, and more than one year of math. That has been a challenge to go out and pick these very different areas. What should they learn and what should they not learn?

It has been fun. We had 35 students the first year and then grew to 60. Right now we are taking 45 students in and they are very motivated, very excited. We can see now the first crowd of people, many of whom are Ph.D. students and are going into interdisciplinary projects to a much higher degree than the ordinary physics and chemistry students would do beforehand.

PSW: Is this now a full graduate program?

Flemming Besenbacher: Yes. We have a 3-year bachelor's, we

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Prof. Flemming Besenbacher in his office at iNano, Aarhus University, Denmark.

To hear Prof. Besenbacher's advice to young scientists, please visit us at the audio/podcast page of http://www.acsnano.org/.

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have a 2-year master's on top of that, and then we have a Ph.D. graduate school with 120 Ph.D. students. There are three ways to get into the Ph.D. program. We have established an honors program, so the very best bachelor's students can now apply directly into the Ph.D. program, with a 5-year Ph.D. program on top of the 3-year bachelor's. Another program is called "4 + 4", so after 4 years of study, there are 4 more years for the Ph.D. without doing a master's. One can do a master's after 5 years and then a 3-year Ph.D. In total, it takes 8 years from entering a university to get a Ph.D. That has been an initiative from the government, to get Ph.D. students finished while they are younger. The average age of our Ph.D. students finishing is about 27.5 years.

PSW: Are people at institutions other than Aarhus University involved?

Flemming Besenbacher: Aarhus is the nucleus. We have an increasing number of students coming [to Aarhus] from around the world after their bachelor's degree for a Ph.D. We have very few [international] students for the first 3 years—it is 95% Danish. We are now discussing a 2-year international master's program, to use that as a mechanism to attract international students to our Ph.D. program. But right now, it is not on the grant yet. The first 3 years is mainly Danes, and then in the Ph.D. [program], it is on the order of 30% international [students].

PSW: Is the undergraduate education in Danish?

Flemming Besenbacher: Yes, that is part of it. The first two years are exclusively in Danish; the third year is in English. That is because in Europe there is something called the "ERASMUS Programme" [European Region Action Scheme for the Mobility of University Students]. There, we see a number of students from Italy, Spain, and Germany spending half a year here. The rule is that as long as there is one international student in the class, we switch to English.

PSW: From what disciplines are faculty involved in the program?

Flemming Besenbacher: It is physics, chemistry, molecular biology, and biology. Right now, we're setting up an increasing number of programs within the area of nanomedicine with people from the medical faculty (that is more on the Ph.D. and postdoctoral level).

Many of my colleagues are trying *desperately* to get their hands on one of these students, because even in molecular biology, for the nanobio projects, they get students that know chemistry, math, physics, and so forth. They're actually much better students for the bio projects, and *vice versa*! It is a great success, in my opinion.

Actually, when we opened the nanocenter, Heine Rohrer[9] and Andreas Engel were up here giving lectures that day. Engel was so excited by the idea that he went to Basel and in January 2008, established a program there.

PSW: Can you tell us about the climate for nanoscience in Denmark?

Flemming Besenbacher: If I speak for my own university, I think we have a number of groups that are doing outstanding work in different areas—nanomaterials, nanobio, and so forth. I think that before we had the nanocenter, it was generally the case that people from different departments were not really interacting. There is no question that the iNANO Center has catalyzed collaboration. Also, we are applying for funds together for new nanobiosensors, drug delivery from nanoparticles, new functional nanomaterials, and so forth. That means that now physics professors, bio professors, and chemistry professors come together and write joint proposals. That also means that the students circulate around the different laboratories.

Nano has become higher on the agenda of the university; the administration of the university has decided to build a 10 000 m^2 building. Right now, we are placed in different departments, and one of the big problems is to get *space*. We're constantly fighting for space, but luckily we have had a lot of support from our Vice Chancellor and Dean. We will start [construction on] our new 10 000 m^2 building now and then we will all move into it. I very much look forward to that!

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PSW: You have strong connections across Europe. Is iNANO a follow-on to CAMP [the Center for Atomic-Scale Materials Physics]?

Flemming Besenbacher: We are part of the "Networks of Excellence" together with 12 partners from Cambridge, Twente, Basel, and others.[10] So, we have close links to other countries. Right now, we are establishing very close links to our Chinese colleagues at the National Center for Nanoscience and Technology in Beijing.[11] At this moment, I'm sitting here drafting a joint proposal with them.

PSW: What are the research goals of iNANO? Are they defined or intended to be general?

Flemming Besenbacher: We have sort of major headlines here: one of them is functional nanomaterials; another is energy materials with nano aspects, solar cells, for example. Other topics are self-assembly of molecular nanostructures, nanomedicine, a program which we call "nanofood", nanotoxicology, and nanoethics.

PSW: What is "nanofood"?

Flemming Besenbacher: Yeah, what's "nanofood"? That is interesting. We have many food-related industries in Denmark, and when I started to go out and talk to some of these industry leaders, I realized that there are a lot of problems related to nano and food. One problem is functional nanomaterials. If you go out to food-producing industries, the first thing you see is a lot of stainless steel (in dairies, breweries, whatever). One big problem there is the development of biofilms. These biofilms can potentially be big risks.

One project we have right now is to develop nanocoatings on surfaces that

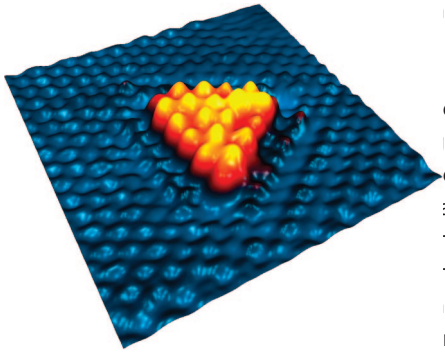

Figure 2. Atomic-resolution scanning tunneling microscope image of a MoS_2 nanocluster on Au{111}. Figure courtesy Jakob Kibsgaard and Flemming Besenbacher. Adapted from data described in ref 14.

prevent or reduce the formation of biofilms on surfaces. We have pretty good results, which will be tested in a local dairy here soon.

Another big area in relation to food is biosensors for detecting pathogens — to compare nanosensors to ordinary sensors. If you want to test for *Salmonella* now, that typically takes 24 h in a laboratory. With some nanobiosensors, you may be able to do it in minutes or seconds.

There are interesting aspects related to delivery, such as nutritional intake — the uptake of proteins and vitamins. Can that be done in more efficient and intelligent ways? Food delivery is closely related to the delivery for medicines. We have the same approaches: formulated nanoparticles, micelles, and so forth.

PSW: How are industrial connections established? Do the companies have some say in what the students work on?

Flemming Besenbacher: Denmark is a very small community, 5.5 million people. You basically know everybody. To a large degree, it is personal contact from me to many of the CEOs in different companies. I've had the pleasure of collaborating with Haldor Topsøe (a catalysis company) for more than 25 years [Figure 2].[12,13] With other companies, we have to get the contact established. Typically, we go out and give a presentation to the research directors, and some of them are interested. It may start as a low-profile project with a cofi-

anced Ph.D. student. It might grow to larger joint program.

I keep saying, "If you come in and invest in basic science here, you should ive us the freedom to work in the area ou're interested in (drug delivery, catalysis, and so forth). Look at this as an nvestment in fundamental science, an nvestment in young people. We're appy to work with you, and if we file ny patents you can get the freedom to operate within your field of interest. But, we don't want you to call every morning and say, 'Can I get the new results from last night?'" They have basically accepted that.

PSW: Do your students get hired into those companies?

Flemming Besenbacher: Often there is a correlation that if a student has been working with a company, then he or she will get an offer from that company. Denmark's biggest problem right now is lacking a skilled labor force. Right now, in Denmark, we would like to have more "brain gain", people coming to Denmark. The students here have absolutely no problem getting jobs, absolutely no problem. I think that the system with this 8-year Ph.D. is such that we are losing very few Ph.D. students before they finish. They simply finish and then they go out for a job or abroad for a postdoc.

PSW: Is engaging the community a part of the Center?

Flemming Besenbacher: Yes, we have the strong support from the municipality of Aarhus, and also the region of Aarhus. I spend a lot of time going out to the public and giving general lectures about nano, telling them what it is. Some people are scared of nano, but I try to tell them that it is not that dangerous.

PSW: Do you have a particular message that you try to get across?

Flemming Besenbacher: When the U.S. National Nanotechnology Initiative was launched, Bill Clinton gave a speech[15] where he said that nano may lead to the next industrial revolution. I think that there are many areas on

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longer timescales where nano can contribute in a very positive way to society.

One of my main messages is to avoid hype. It does not help that on a short time scale we say that we can cure cancer, we will develop solar cells, or we can get rid of fossil fuels. It does not help the area and it is damaging.

I think that we *should* see this as potentially leading to the next industrial revolution. The key here is investing in fundamental nanoscience right now. Out of that, we in universities should try to patent the ideas we have that may potentially be relevant for technology. Out of our 120 Ph.D. students, one-third are cofunded with an industrial partner who pays one-third of the student's Ph.D. stipend, which is a very interesting aspect.

My method is: "Here are a lot of different areas that I'm trying to describe as much as possible. Where are the potential advantages?" But also, I try to say in an honest way, "There are potential risks here, which we have to take seriously. Spreading of carbon nanotubes into the environment and uptake of nanoparticles and carbon nanotubes into cells may lead to toxicological effects." Again, for that area, we established a program with people from our medical department, because in my opinion, the dose of the particles is a critical parameter. I'm not particularly impressed by some of the toxicology pa-

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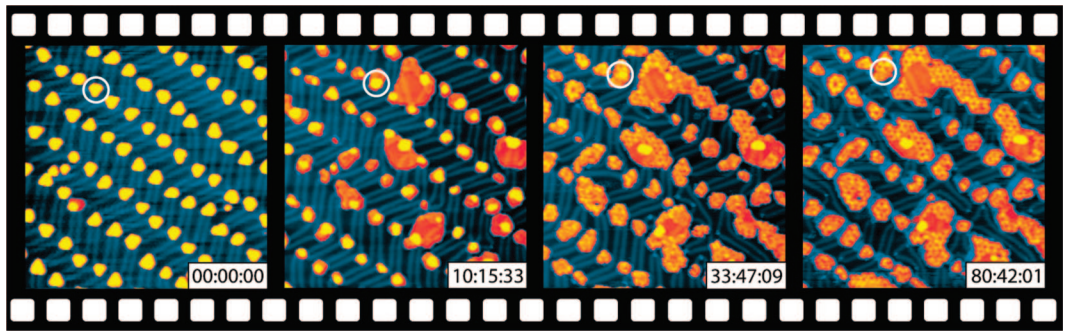

Figure 3. Frames from a ~80-h time-lapse series of STM images (700 Å × 700 Å) of metallic Co nanoclusters reacting with gaseous H_2S to form CoS. One reference cluster is marked by a circle and the time is indicated on each frame (h:min:s). Reprinted with permission from reference 16. Copyright 2008 American Physical Society.

pers that have been published so far. I think a lot of basic science is called for before we can make any major regulations.

PSW: What do you see as the biggest impacts of nanoscience on society?

Flemming Besenbacher: I personally believe that, if we could step 20 years ahead, the medical area has the potential to be a major breakthrough in the way we cure diseases, and also in diagnostics. I know the time scale is fairly long, but I see a lot of potential there.

PSW: Do you see a big challenge in making that a reality?

Flemming Besenbacher: Not really. We have already in the iNANO Center a few patents, for example, on drug delivery. So, what are the barriers for the circulation of nanoparticles, penetration into cells, and release of drugs? I think that we are demonstrating in animal models of disease that it actually can be done. Of course, it is a question of scaling up and further testing. I do not think that there are major stops that would prevent us from progressing along these lines. Again, biosensors on the bedside, testing for a *number* of things instead of taking a blood sample and running to the laboratory, investigating, then coming back 4−10 h later. If you could do some of these things at the bedside, it would be fantastic.

> The key is investing in fundamental nanoscience right now.

PSW: Going back into history a bit, I remember the 1990 STM meeting [Fifth International Conference on Scanning Tunneling Microscopy, STM'90], when your group just burst on the scene with the first STM movies of dynamics [Figure 3].[2] How did that come about?

Flemming Besenbacher: That [meeting] was in Baltimore.

In the science faculty in Aarhus, we have always had the infrastructure to allow us to build our own research equipment. We have a very good mechanical workshop and a very good electrical workshop, both outstanding groups. We have been building equipment ourselves for many years with a background going back to accelerator technology. When we started to build the STMs in Aarhus, I got in contact with one of my very good colleagues here, Erik Lægsgaard.[1] Erik had an outstanding person for doing this combination of mechanical, electronic, and information technology.

The secret behind the Aarhus STM is nothing else than that it is a very small and compact design, which leads to a very high mechanical resonance frequency, meaning that we are *much* less sensitive to vibration. It is a concept back from the late 1980s; the core of this microscope is basically the same today. Now, we are testing new electronics that will allow us to record 25 frames per second. We are also in the process of building a high-resolution AFM [atomic force microscope] with atomic resolution.

PSW: You are still working together on advancing the field?

Flemming Besenbacher: Yes. We still have this infrastructure, and we are still building our own equipment.

SPECS GmbH is now selling our STM commercially, because we did not want to do that. We simply gave SPECS a license to sell the STM.

PSW: Do you have advice for young scientists?

Flemming Besenbacher: I myself studied physics. If I could choose today, I would definitely go into nanoscience. I think it is a *fantastic* area. To me personally, I think many of the advances in the next 20 years will be at the borderline of physics and chemistry, physics and medicine, physics and biology. I think the nano area again is a fantastic area. I think that hard work and dedication combined with some of the inspiration we have here is... well, I just like it and enjoy every day. I also think the young people that we have in nanoeducation—it is fantastic, and they seem to like it also. I'm very pleased with that.

[*Literature citations and figures were added after our conversation to assist*

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and to direct the reader to relevant publications.]

— Paul S. Weiss

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REFERENCES AND NOTES

1. Besenbacher, F.; Lægsgaard, E.; Mortensen, K.; Nielsen, U.; Stensgaard, J. Compact, High-Stability, Thimble-Size Scanning Tunneling Microscope. *Rev. Sci. Instrum.* **1988**, *59*, 1035–1038.
2. Jensen, F.; Besenbacher, F.; Lægsgaard, E.; Stensgaard, I. Dynamics of Oxygen-Induced Reconstruction of Cu(100) Studied by Scanning Tunneling Microscopy. *Phys. Rev. B* **1990**, *42*, 9206–9209.
3. Ruan, L.; Besenbacher, F.; Stensgaard, I.; Laegsgaard, E. Atom Resolved Discrimination of Chemically Different Elements on Metal Surfaces. *Phys. Rev. Lett.* **1993**, *70*, 4079–4082.
4. Otero, R.; Rosei, F.; Besenbacher, F. Scanning Tunneling Microscopy Manipulation of Complex Organic Molecules on Solid Surfaces: A New Tool for Nanoscience and Nanotechnology. *Annu. Rev. Phys. Chem.* **2006**, *57*, 497–525.
5. Otero, R.; Lukas, M.; Kelly, R. E. A.; Xu, W.; Lægsgaard, E.; Stensgaard, I.; Kantorovich, L. N.; Besenbacher, F. Elementary Structural Motifs in a Random Network of Cytosine Adsorbed on a Gold(111) Surface. *Science* **2008**, *319*, 312–315.
6. Weigelt, S.; Bombis, C.; Busse, C.; Knudsen, M. M.; Gothelf, K. V.; Lægsgaard, E.; Besenbacher, F.; Linderoth, T. R.; Besenbacher, F. Molecular Self-Assembly from Building Blocks Synthesized on a Surface in Ultrahigh Vacuum: Kinetic Control and Topo-Chemical Reactions. *ACS Nano* **2008**, *2*, 651–660.
7. Andersen, E. S.; Dong, M.; Nielsen, M. M.; Jahn, K.; Lind-Thomsen, A.; Mamdouh, W.; Gothelf, K. V.; Besenbacher, F.; Kjems, J. DNA Origami Design of Dolphin-Shaped Structures with Flexible Tails. *ACS Nano* **2008**, *2*, 1213–1218.
8. Interdisciplinary Nanocience Center. http://www.inano.dk/.
9. Weiss, P. S. A Conversation with Dr. Heinrich Rohrer: STM Co-Inventor and One of the Founding Fathers of Nanoscience. *ACS Nano* **2007**, *1*, 3–5.
10. Frontiers. http://www.frontiers-eu.org/partners/.
11. Weiss, P. S. A Conversation with Dr. Chunli Bai: Champion of Chinese Nanoscience. *ACS Nano* **2008**, *2*, 1336–1340.
12. Helveg, S.; Lauritsen, J. V.; Lægsgaard, E.; Stensgaard, I.; Nørskov, J. K.; Clausen, B. S.; Topsøe, H.; Besenbacher, F. Atomic-Scale Structure of Single-Layer MoS_2 Nanoclusters. *Phys. Rev. Lett.* **2000**, *84*, 951–954.
13. Lauritsen, J. V.; Bollinger, M. V.; Lægsgaard, E.; Jacobsen, K. W.; Nørskov, J. K.; Clausen, B. S.; Topsøe, H.; Besenbacher, F. Atomic-Scale Insight into Structure and Morphology Changes of MoS_2 Nanoclusters in Hydrotreating Catalysts. *J. Catal.* **2004**, *221*, 510–522.
14. Lauritsen, J. V.; Kibsgaard, J.; Helveg, S.; Topsøe, H.; Clausen, B. S.; Lægsgaard, E.; Besenbacher, F. Size-Dependent Structure of MoS_2 Nanocrystals. *Nat. Nanotechnol.* **2007**, *2*, 53–58.
15. Pres. Clinton's speech at Cal Tech in 2000 announcing the National Nanotechnology Initiative is available online at http://web.archive.org/web/20001205172900/http://www.whitehouse.gov/WH/EOP/OSTP/html/0022_5.html.
16. Kibsgaard, J.; Morgenstern, K.; Lægsgaard, E.; Lauritsen, J. V.; Besenbacher, F. Restructuring of Cobalt Nanoparticles Induced by Formation and Diffusion of Monodisperse Metal-Sulfur Complexes. *Phys. Rev. Lett.* **2008**, *100*, 1–4.