Mr. President,
dear Professor L'Huillier, dear Anne
liebe Kollegen und Studenten, lieber Herr Kempe,
meine sehr verehrten Damen und Herren!

It's my privilege to explain to our university members and to the public in general, why this faculty has chosen to bestow an honorary doctorate on Professor Anne L'Huillier.

Anne L'Huillier studied mathematics and physics at the Ecole Normal Supérieure from 1977 to 1981 and obtained master's degrees in both subjects, and, in addition, a teaching degree in mathematics.

She did a Ph.D. in physics in Saclay under the supervision of Professor Mainfray who was a pioneer in superstrong lasers. Subsequently, in 1986, she became a permanent researcher in Saclay.

She kept that position until 1995 when she became associate professor in Lund, Sweden and married an almost as well-known colleague, Professor Claes-Göran Walström. The couple has two children. In 1997, Anne L'Huillier was appointed full professor.

Anne L'Huillier has an extraordinarily distinguished scientific record. She has authored and co-authored some 190 publications that have been cited 16.000 times. Her h-index is exceeds 60, meaning that 1/3 of her papers were cited more than 60 times. The most heavily cited paper has more than 2500 citations, but I dare to say that this is not her most significant paper, although it *is* tremendously important as we will see. There are at least three other papers I would rank even higher: The discovery of high-harmonic generation – L'Huillier and high-harmonic generation are synonyms – the discovery of non-sequential double ionization and the discovery that high harmonics can magically form attosecond pulses.

It took a while until the community started to acknowledge the outstanding contributions of Professor L'Huillier. Meanwhile she has received a series of honors and prizes. I mention just two: In 2011 she became a member of the Legion of Honor, the highest French Order of Merit. Two years ago, she received the Carl Zeiss Award. Back then we used the opportunity to invite her to Jena and had the pleasure to listen a lecture of her here in this hall. In the same year, she received her first and so far only honorary doctorate from Université Pierre et Marie Curie.

Why then an honorary doctorate from the Physikalisch-Astronomische Fakultät of Friedrich Schiller University in Jena?

The explanation is actually as simple as sound: There is rarely any other person on this planet whose discoveries have had a similar impact on the present scientific programs at our faculty. The research programs of more than five research groups take advantage of Professor L'Huilliers discovery of high-harmonic generation. This is certainly reason enough for an honorary doctorate, in particular if you factor in how many students and also how many research Euros are involved in these programs. No question, we certainly could stop the laudation at this point.

But we should not! For the reason that the story behind Anne's discovery of high harmonics and the discoveries that led to the emergence of an entirely new field – attosecond laser physics – is too interesting not to be told this evening. We will concentrate on Anne's earlier work because even the specialists in the audience likely don't know the interesting respective facts. And for the same reason we start with another discovery Anne made more than 30 years ago – a discovery that has kept busy numerous colleagues to the present day.

I am quite confident in my ability to evaluate Anne L'Huillier's contributions, in particular also the early ones. I joined the field of strong-field laser physics in 1991 when I became a diploma student at the Max Planck Institute of Quantum Optics, the MPQ. Scientifically, I was a blank slate. The group in which I worked was also pretty new to the field. We had no own stocks and thus no bias. Thus I would watch the scientific battle scene, on which the dust after the first strikes began to settle with a fresh mind.

There was above-threshold ionization – the good old photo effect, which Einstein famously explained – the good old photo effect under extreme conditions. Above-threshold ionization was discovered by Pierre Agostini and coworkers in 1979: More photons – quite a few more! – than necessary for ionization can be absorbed by atoms subject to intense laser radiation. A nightmare to the, by then, young but so far very successful theory of multiphoton processes. – And more such nightmares, more severe ones, were about to arrive.

In our group we would discuss the alternative attempts of a theoretical interpretation of above-threshold ionization: Floquet theory, all varieties of Keldysh theory, Kramers-Henneberger picture, and – with an uncomfortable feeling – tunneling and classical models. There was even the suggestion of capitulation: solve the Schrödinger equation numerically and state that beyond that there is nothing left to be understood.

However, there were two other effects – and I have been lucky enough to discover a third one – so there were three effects so fascinating that even I as a young student thought it would a shame to accept them with the shrugging remark: „well, it comes out of theory, it is a consequence of Schrödingers equation".

Both effects were discovered by a lady of whom we only knew the name: Anne L'Huillier. You know: At the MPQ we had quite a few visitors every month; and within a year or two, I had seen and heard all the big names in the field at least once. Actually, the small group in which I was working was the only at the institute that was active in strong-field laser physics. In fact – hard to believe today – we had the only femtosecond laser at the MPQ.
In this way, I learnt to know most of the pertinent more and less famous visitors at our poster personally. The exception being – Anne l'Huillier. Only six or seven years later, I would meet her personally. What I want to say with this: Anne's fame roots solely in the quality of her work and the profoundness of her discoveries – not in ringing bells and making noise. Also, we will see that none of the two famous effects she discovered was published in Nature or Science, high-harmonic generation even not in the Physical Review Letters, but in journals with an impact factor around three. Well, back then, we didn't know what an impact factor should be.

We all know, of course, that Anne is famous for her discovery of high-harmonic generation and related work. That's why I start with this other major discovery she made. And this discovery is particularly telling with respect to Anne's tedious approach, but also with respect to the conception by the community.

In the early 1980s, Anne measured the yield of photoions as a function of the laser intensity used to produce them. I guess, she had to do that as kind of a lab work project. Everybody in the field knew what to expect: The number of detected ions should grow proportional to the n-th power of the laser intensity. At the wavelength used, you need 13 photons to ionize neutral Xe and another 20 to ionize the Xe ion once more. If one plots the data on a double logarithmic plot, the data points should lie on a line, the slope of which corresponds to the number n of photons required for ionization. Once everything is ionized, the slope will bend, of course.

To great surprise, however, much more doubly charged ions than expected were found at relatively low intensity. The feature may look minor. But remember, we use logarithmic scales. The deviations from expectations are huge, many orders of magnitude! The effect was given a name by the community: Anne L'Huillier' beautiful knee. I guess that people, aware of Anne's a little bit reserved personality tried to tease her to a certain degree in a mixture of respect and disrespect.

When I read Anne's paper in Physical Review A for the first time, I was impressed by the clarity not only of the experiment, but also by the clear, yet tedious and daring theoretical analysis. Anne invoked double ionization directly from the neutral atom as an alternative pathway to sequentially removing an electron first from the neutral atom and then from the singly-charged ion. By fitting the corresponding rate equations, she even assigned a *cross section* to direct, or non-sequential, double ionization. Without this number for the cross section the story would probably have evolved differently.

When non-sequential double ionization is referenced today, people often cite a paper by Lou DiMauro's and Ken Kulander's group. Their paper was published almost ten years later. To date, their paper has been cited almost 900 times, Anne's Physical Review A, with almost ten years of head start, about 300 times, the original Letter to Physical Review even only less than 150 times. In fact, also the article on Wikipedia on Anne l'Huillier and a few colleagues seem to have difficulties to acknowledge Anne's accomplishments.

Why this? One colleague once referred me to a paper of Peter Lambropoulos, a towering figure in the theory of conventional multiphoton theory. In his paper, he discussed Anne's paper in a Physical Review Letter and he pointed out that scaling arguments reveal that the cross section she gave is many, many orders of magnitude too high.

The colleague with whom I discussed would conclude that Anne's paper was wrong. That's nonsense: The only thing Lambropoulos proved was that Anne L'Huillier's paper is as many orders of magnitude more interesting than previously anticipated as the cross section deduced by Anne deviates from conventional theory. Therefore it was so important not just to show the effect, but to assign this number, this cross section to it.

By the way: I never understood why someone would consider L'Huillier's paper less valid than DiMauros: If people would read the papers they cite, they would discover that DiMauro's paper was written to *disprove* the recollision model for non-sequential double ionization proposed by Paul Corkum. But Corkum was proven right in 2000. By the way, the respective Nature paper, half as old as Anne's, has been cited twice as often as hers.
Does this devaluate DiMauro's paper? Of course not! It still reports one of the best measurements in the field.

Actually, hard to believe today, there were more papers fighting against the recollision interpretation. These papers would claim that they finally found the explanation for Anne's effect. And when recollision was finally confirmed almost 20 years after Anne's experiment, they would say the knee in Xenon and Helium have different physical origin and ignore the evidence for the opposite. Well …

That is the reason why we decided to cite non-sequential double ionization on the honorary doctorate certificate.

What next? High-harmonic generation! That's a huge story, so huge that there is no question that the one or the other *application* of high-harmonic generation will once be decorated by a Nobel prize. Whether the very discovery of high-harmonic generation will also be honored this way, I am not so sure. Prizes not only reward outstanding scientific work, they seem to reward also excellence in networking and politics.

Anne and her collaborators discovered high-harmonic generation in 1988. A remarkably simple experiment: Focus an intense laser in some gas at sub-atmospheric pressure and you receive the harmonics, the overtones of the laser radiation, beyond the 30th order back then, a few hundred orders today. A complete surprise! Everybody had expected that the harmonic intensity would decrease more or less exponentially with increasing harmonic order. If so, there wouldn't be any chance of observing – not to speak of applying! – much more than a handful of harmonics.

And the scientific community? Well, in particular the colleagues in the US say that Charles Rhodes has discovered high-harmonic generation – and, sure enough, his paper has collected more citations than Anne's. Indeed, he measured harmonics. However, to me it is still

not obvious whether his effect has much to do with what we consider high-harmonic generation today. After all, Charles Rhodes used a more than 4 times shorter wavelength than Anne L'Huillier a few months later and we know meanwhile that things scale quadratically with wavelength in high-harmonic generation.
The experts in the audience also know about the narrow parameter range of high-harmonic generation: If you do an experiment with parameters that differ by a factor of 20, well, then it is not really obvious that you see the same thing.
But even if it were so, one would have to say that Charly Rhodes took the wrong direction twice: He proposed to use shorter and shorter driving wavelengths where we know today that, counter-intuitively, one should use long wavelengths – as Anne did. And Rhodes even failed to recognize the hallmark of high-harmonic generation, the flat slope of the spectrum's envelope, the plateau. He rather interpreted the changing slope of his spectra's envelope as a depression due to atomic absorption lines.

High-harmonics captivated physicists immediately, the more, the more we learned about their properties: They are nicely collimated and perfectly coherent in space and time, just as one would expect of harmonics of laser radiation.

Learning to use them, however, turned out to be a formidable . People were unhappy with the low conversion efficiency. Earlier I said that the harmonics are remarkably strong. Yes true, but in absolute numbers, it is roughly one in a million.
When I was a graduate student, on elder scientist would tell me that it is an old farmers' rule that every laser has an average power of one Watt. Then, the harmonic radiation will have just a Microwatt. Well, times have changed, not least for the work of, for example, my colleague Jens Limpert whose lasers drive harmonic conversion with a photon flux that starts to rival the flux at large-scale synchrotrons.

Another colleague, Christian Spielmann, uses high harmonics for nano-scale imaging without lenses – coherent diffraction imaging. My group pursues optical coherence tomography for cross-sectional imaging, also on the nano-scale. And this is by far not the end of the list, not even in Jena.

The best part at the end: When people saw the comb of harmonic lines, a few were reminded of mode-locked lasers: A laser cavity can support only standing waves that fit squarely between the laser mirrors, meaning that the distance between the mirrors must be an integer multiple of the wavelength. Therefore, the spectrum of a laser is a comb of discrete frequencies which differ by the speed of light divided by twice the distance between the mirrors. When we add many slightly different frequencies, short pulses emerge. Femtosecond lasers work like this. Well, one has to say that this is not the entire truth: Rather, short pulses will be produced only if all these frequencies are in phase.

So people saw the harmonic comb and wondered whether they are in phase – and make *attosecond pulses*. Attosecond pulses! The time scale on which electrons move in atoms, molecules and solid state material! Attoseconds: the fastest timescale of all earthly phenomena, the fastest timescale in chemistry and biology. The holy grail of ultrafast laser physics.

But nobody had a clue how to measure such short pulses: The extreme ultraviolet is very demanding technology. So the theorists were the first to give an answer. They solved the Schrödinger equation numerically and checked whether the harmonics are in phase.

I remember the respective viewgraph a visitor was presenting at the Max Planck Institute of Quantum Optics around 1995 as if it would had been yesterday. Actually, I remember the viewgraph but not the scientist who showed it. The graph showed that the phases of the harmonics jump wildly between 0 and 360 degrees. Only towards the end of the spectrum, where the harmonics are weak and probably not of much use, they are in phase. No attosecond pulses!
The visitor – I believe to remember a slight triumph in his voice; the idea with the attosecond pulses was apparently not his baby – the visitor went on to emphasize what was evident to his audience anyway: The calculation was made for a single atom; the reality surely will be worse – no attosecond pulses!

And then this paper by Anne L'Huillier and company. Her paper built on one that she had published two years earlier and in which the role of phase matching in high-harmonic generation was explained: how the millions and billions of atoms in the laser focus team up the produce a macroscopic beam of XUV radiation. It's the paper I mentioned in the beginning, the paper with the 2500 citations.

In 1996, Anne and her colleagues would use their theory to predict that phase matching will miraculously clean up the phases of the harmonics. What a fantastic prediction! The prediction proved right: in 2001 the duration of attosecond pulses was measured for the first time and – lived happily ever after.

Indeed, a story like fairy tale – but a true story. We are very delighted to have the hero of this story with us this evening: Welcome Professor L'Huillier in Jena!

Prof. Dr. G. G. Paulus

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