Discurso de investidura como Doctor "honoris causa" del Excmo. Sr. D. Rainer Blatt

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Excelentísimo y Magnífico Rector, Autoridades Universitarias, Profesores, Señoras y Señores:

It is a great honor and immense pleasure for me to be receiving an honorary doctorate from the Universidad Complutense, one of the oldest and most distinguished Universities in Europe and in the world.

My dear friend Miguel Angel Martin-Delgado has already mentioned many of my career steps and achievements in his laudation. I will try to add a little information to that, giving you perhaps a bit more insight into how this was accomplished. Mostly, this is due to the efforts of the great teams with which I had the pleasure to work over several decades, and due to collaborations with many distinguished colleagues.

When I started my studies at the University of Mainz, I wanted to become a high school teacher of Mathematics and Physics. As a part of my training, I was teaching part-time at a high school in parallel to studying. While I generally enjoyed working with high school students, in the course of my studies, my interests gradually changed and fundamental physics drew my attention more and more. Eventually, I decided to focus on physics and to pursue a PhD in physics.

At that time, there was a strong experimental group at the University of Mainz, investigating charged atoms (i.e. ions) and elementary particles, in particular electrons and their positive cousins, positrons, in a device, which they called a "trap". In fact, they were able to catch small clouds and even individual charged particles and keep them for minutes and even hours right at your fingertips for measurements. This technique absolutely fascinated me, because it provided an ideal tool to study quantum physics at the most elementary level – just a few quanta available in free space, all yours to admire and to work with. Quantum physics with atoms (and their charged sibyls, atomic ions) thus had a very concrete meaning to me and I was able to learn and master these techniques.

Having particles readily available for an extended time allows you to measure their properties in a refined way and with a very high precision. Therefore, such experiments are the basis for time keeping at the atomic level – that is for atomic clocks. With them, I learned to love the art of making measurements – that is metrology, in this case with atomic ions and radio frequencies.

Being a young postdoctoral fellow, I was eager to learn more about precision measurements. With the availability of tunable lasers in the 70s it was obvious that the next step towards higher precision needed precisely controlled optical (laser) radiation. The world expert at that time was John L. Hall at JILA in Boulder, Colorado, in the United States (Nobel laureate of 2005, for the laser frequency comb technology). Therefore, I joined him in 1982 as a postdoc to learn precision laser technology.

Precise measurements are possible, when atoms do not move. Around that time in the early 80s, teams in Germany and in the US had developed cooling techniques using laser light. They allow one to freeze the motion of atomic particles and a postdoc colleague and I, together with Jan Hall, were able to demonstrate stopping of freely moving (neutral) atoms – another important technique and ingredient for precision measurements.

Being virtually infatuated with the possibility to trap individual atomic particles and now armed with the knowledge of precision laser technology, I joined the Hamburg team of Peter Toschek and Werner Neuhauser, where we trapped and investigated single Ba+ ions. We illuminated these ions with a laser beam and removed their residual motion in the trap by laser cooling, such that they finally resided in the center of the trap with an uncertainty of only a few nanometers – a few millionths of a millimeter! These atoms fluoresce, that is, they emit their green light, which we observed with our naked eyes using a microscope. The ability to actually "see" a single atom radiating never ceased to fascinate and mesmerize me. Even today, it is still with awe, when I see the light from a single particle. You are very welcome to visit our team in Innsbruck, where you can join the club of the single-ion watchers.

Being able to confine a single atom with such a high precision and to examine it in situ allowed us for the first time to observe the proverbial quantum jumps, which had been proposed in 1913 by Niels Bohr in conjunction with his model of the atom. These jumps became directly visible as a blinking atom, that is, the radiating electron jumps back and forth between two quantum states of the atom. Stunningly, absorption and emission

events became immediately visible and available to the experimentalist – a dream came true.

The combination of a single trapped and laser-cooled particle with precision laser technology and using quantum jumps for the measurement eventually led to the realization of an ultimate frequency standard in the optical domain. Such devices are 100-1000 times more precise than the best atomic clocks using microwave frequencies, and they are now routinely available in standard labs and will be commercially available soon.

Since the development of these techniques focused on atomic clocks, in the late 80s and the early 90s it was not so clear what else could be done with that unique combination of techniques. Around that time, I tried to extend the methods and techniques to other fields of physics and to measurements in general. In a discussion in 1990, my friend Bill Phillips (NIST Gaithersburg, Nobel prize 1997 for laser cooling) asked me a very simple question: "What happens when you place a single trapped ion in a standing wave?" In order to answer this question, I had to make certain approximations in my calculations. However, the result appeared quite interesting, because it seemed possible to cool the trapped atomic ion better than with a traveling wave.

Since my time as a postdoctoral fellow in Boulder, I had kept a close collaboration with theorists, in particular with my friend and colleague Peter Zoller at the University of Innsbruck. I contacted him and asked for his advice on how to treat this problem more generally. While he did not have an immediate answer, he gave this task to a young visiting student – Ignacio Cirac from the Theoretical Physics at Universidad Complutense. Ignacio tackled the mathematical problem, and came up with a general solution and an elegant formalism, which provided the toolbox for many calculations we then did between 1990 and 1996. With Ignacio Cirac and Peter Zoller the theoretical fundamentals were then established that provided the basis for the experimental work in my group in Innsbruck.

On one of our frequent visits to Peter Zoller, who was then a professor at the University of Colorado in Boulder, Peter, Ignacio and I attended the International Conference on Atomic Physics (ICAP) 1994 in Boulder, Co, where we for the first time learned about quantum information processing in a talk by Artur Ekert (Oxford and Singapore). In that year, Peter Shor (AT&T) came up with an algorithm, in which he showed that the notorious factoring problem could be efficiently solved with a quantum machine, doing the computations. Breaking down large numbers into a product of prime numbers is a

hard problem and the basis of today's encryption algorithms. Therefore, if a quantum computer were available, the security of all electronic communication might be endangered and thus this result got a lot of attention. Such a quantum machine (or a quantum computer) could be realized by a quantum analog of the Boolean XOR operation between two quantum bits (CNOT gate) and some quantum operations on individual quantum bits. Earlier ideas about how to solve hard quantum problems with a quantum device had been discussed already in the mid 80s by Richard Feynman and David Deutsch, mostly in connection with simulations of quantum mechanical processes. However, at that time this was considered exotic since no hardware existed to realize such quantum operations.

Upon learning about this new field in 1994, we realized immediately that trapped atomic ions could be used as the carriers for quantum information and precision laser technology, formerly used for metrology, could be employed for the quantum operations. Eventually, Peter Zoller and Ignacio Cirac came up in 1995 with the first realistic and viable proposal how to realize the crucial quantum gate operation. This was a major breakthrough and my group and I immediately embarked on the implementation of this idea.

Thus, around 1994 was the real start of what we now know as Quantum Information and the quest for a universal quantum computer.

What, actually, is Quantum Information? And what can we do with it?

For this, let us briefly review what we all know from classical information processing: The tiniest bit of information is called precisely that: a "bit", which is short for binary digit. By this, we mean the information contained in a switch position that is either "up" or "down" or, in modern mathematical language, just a Zero or a One. Complex information such as text messages, emails, images or voice messages can be cast into strings of these zeros and ones. Starting with such a string as an input, classical information processing acts by changing the string according to rules that we cast into a program and finally we obtain an output string, again composed of zeros and ones, which contains the result of this information processing or of a computation.

Information processing is the basis for all modern data handling and all classical computers that we have today. These classical computers have revolutionized our lives, our industries and the world during the past decades. However, in the 80s Richard

Feynman already realized that we have some problems, for example in the calculation of quantum mechanical problems that are very difficult to handle with classical computers. The reason for this is the notion of a quantum mechanical superposition: While in a classical world a switch can be only in the “up” or “down” position, a quantum switch, say an electron in two quantum states of an atom, can be in what we call a “superposition”. That means, prior to a measurement, it is not only that we do not know where the electron is (in either the “upper” or the “lower” state), but rather that we have to assume that the electron is in both states at the same time. Such superpositions are very counterintuitive at first. However, all experiments that have been done over the last 100 years, clearly tell us that this is true.

Mathematically, we understand superpositions by describing all quantum phenomena in a wave picture. Doing quantum calculations on a classical computer then requires that all possible superpositions are described and stored in the computer memory. For complex problems, as for example the calculation of large molecules and the simulation of quantum processes, this requires a memory size and a computing power, which is classically simply not available. Therefore, Richard Feynman suggested that we use quantum elements directly to build the quantum hardware that does the simulations and computations.

Now, with the proposal of Ignacio Cirac and Peter Zoller in 1995, for the first time a realistic quantum computer implementation seemed in reach. While exotic and seemingly strange, a few groups embarked on this journey toward a quantum computer device. However, it took about seven years, until we and a competing group led by David Wineland at NIST in Boulder (Nobel laureate of 2012 for controlling single atoms), were able to realize the gate operation between two different ions, now used as quantum bits in a quantum register. In the meantime, another technology, based on superconducting circuits became available as a quantum computer technology. Since then, many more platforms have been suggested and investigated as candidates for a quantum information processor. Today, there are about four or five different technologies available for this, and the most promising ones are still the trapped ion and the superconducting circuit technologies.

Where do we stand and what has been achieved in the last fifteen years?

After the groundbreaking demonstrations of quantum gate operations in the early 2000s, the early focus of work in my group and in other groups around the world was on fundamental research. In particular, we focused on the creation of highly non-classical states, which can be readily programmed and achieved with a quantum processor. We were excited about non-classical states because with quantum operations we can create quantum correlations between separated atoms, which leads to the following consequences: When one measures the state of one atom in one site, the state of the atom at the other site is immediately defined and known. Albert Einstein, who pointed out the possibility of this strange behavior in a famous article in 1935, called this phenomenon "spooky action at a distance". Erwin Schrödinger coined for this the expression "entanglement" since the state of one atom at one site cannot be changed or measured without affecting the atom at the other site – their states are intricately interwoven, or simply "entangled".

It took about 50 years to detect entanglement with photons and theorists came up afterwards with clever protocols of how to use this feature for quantum communication. In a milestone experiment, the group led by Anton Zeilinger (then in Innsbruck) realized "quantum teleportation", the transfer of quantum information with photons in the late 1990s. Based on splitting a single photon in two correlated photons this was a stochastic protocol with a relatively small success probability.

With the quantum information processors, however, we for the first time had the possibility to create and to manipulate entanglement between remote sites at the push of a button. This allowed us to demonstrate quantum teleportation with atoms, and we could show that with entangled atoms metrology, the science of measurement, can be improved – quantum metrology was realized. Soon after this, we were able to realize a small quantum computer with a quantum register of 8 qubits, which we showed to be fully entangled – the first quantum byte was born. With further improvements, we demonstrated Feynman's visionary dream of doing quantum simulations with a quantum machine. In collaboration with the group of Enrique Solano at the University of the Basque Country in Bilbao, we simulated the Dirac equation, which describes the relativistic behavior of quantum particles. Moreover, with Enrique Solano, Jorge Casanova and Juanjo Garcia-Ripoll (at CSIC Madrid) we simulated the seemingly paradoxical relativistic

dynamics of quantum particles using our quantum devices. Such demonstrations made use of some special features available with our quantum systems, and are generally called analog simulations, which means that we emulate the behavior of physical system with the properties of our device. On the other hand, using more trapped ions as quantum bits and a quantum program, realized by shining a sequence of laser pulses on the ions, we were able to simulate the dynamical evolution of a quantum system. Such a quantum simulation implements a full quantum algorithm and works for any problem, realizing a universal quantum simulator simulator in close collaboration with Peter Zoller's team at the University of Innsbruck. In this way, over the last decade, many more computations and simulations were made with our two working quantum computers in Innsbruck.

One of the major research lines of our group was, and is, the realization of quantum error correction. Like any computer, a quantum computer can make errors. While in a classical computer, errors are rare and routinely controlled by error correction circuits, this is not as straightforward in the quantum world. Classical errors appear when a zero is read as a one or a one is recognized as zero. This can be checked by redundancy, for example, by transferring three times the same value (zero or one). If the receiver sees only two times the value, it is assumed that an error has occurred and by majority decision, the two-valued number is taken. This cannot be done in the quantum world since copying the quantum information in order to encode it redundantly requires that one measures the quantum bit first and that would destroy any possible superposition. This is known in quantum physics as the no-cloning theorem. Peter Shor and Andrew Steane among others, who proposed to use entanglement of several quantum bits to create the needed redundancy, pointed a way out of this around 1995 and 1996. Using such a protocol, we were able to show that even the otherwise disruptive quantum jumps can be undone using such a quantum error correction protocol.

For a future quantum computer, however, which will have to work with hundreds and thousands (and more) of quantum bits, quantum error correction will be necessary and the future scalability of quantum devices depends on its availability. To implement this, my team and I decided to look for an optimized way of storing the quantum information in a number of physical quantum bits (in our case a number of trapped ions) to provide the required redundancy for a logical quantum bit. With a clever sequence of measurements, one then can find out, if and where in this register an error has occurred. Knowing this, the error can finally be undone and the quantum information in such a

logical qubit could then be preserved longer than it would usually last in the presence of noise and errors. A very clever and elegant way to encode such a logical quantum bit was conceived here at the Universidad Complutense by my friend and colleague Miguel Angel Martin-Delgado with his student Hector Bombin, who worked out the details of this already around 2006. A close collaboration with Miguel Angel and his Postdoc Markus Müller allowed us, for the first time, to encode a logical qubit in a set of seven quantum bits in an ion trap in 2014. The wonderful properties of this "color code" even allowed us to realize a set of quantum operations on the logical qubit. The close collaboration with the Theoretical Physics Department of the Universidad Complutense (with Miguel Angel Martin-Delgado and Alejandro Bermudez) continues today and we are now on our way to finally create one of my dreams, the "encoded qubit alive", that is a quantum bit that stays alive for the duration of the computation. Once achieved, this will be the basis for future scalability of quantum computers.

Where do we go and what can you expect from quantum information processing?

While quantum information processing was considered an exotic possibility in the 1990s, it has matured during the last two and half decades to the point, that it is now a major research line in physics and close to being commercialized. Quantum computing time can already by bought and worldwide efforts are underway to implement more and more quantum technologies. During the last decade, it was realized that quantum technologies offer a number of advantages beyond what we thought at first.

Once a curiosity, entanglement has become an entity, which can be used now as a resource. First demonstrated with photons, its application to quantum communication is well advanced and there are already quantum devices commercially available, which make use of specific quantum procedures, so-called protocols. They are inherently safer than their classical counterparts, and they allow one to interconnect quantum devices. For this, relaying quantum information over long distances is necessary. Therefore, the development of devices receiving and transmitting quantum information (so-called quantum repeaters) is currently of high priority and many laboratories in the world are working on that.

As has been shown by us and many others, quantum protocols can and will enhance precision measurements beyond what is classically possible. Currently, this seems still exotic, but in my opinion, such technologies will revolutionize our measurement

capabilities for years to come. These possibilities are well recognized by companies and national standard laboratories and therefore, both quantum communication and quantum metrology are well on their way to be applied and commercialized. A little bit further remote are the chances offered by quantum simulations. However, with a few years of further development, quantum simulations will be the first realm, where quantum devices will clearly surpass the capabilities of classical simulators. Applications of this are wide-ranging, from scientific problems in solid-state and high-energy physics, to quantum chemistry and material science. The Holy Grail, however, is the universal large-scale quantum computer of which we already have a few small working systems in the world. Currently, the registers consist of a few tens of quantum bits, with a few hundred quantum gate operations at best, and quantum error correction not yet implemented. There are worldwide efforts, if not races, underway to realize a large-scale quantum computer, mostly based on superconducting or ion-trap platforms. In fact, there is currently a fair amount of hype about their realization, with big players leading the way and many start-up companies trying to catch up and get a piece of the cake.

Just a few months ago, Google at Santa Barbara, announced that it has achieved what John Preskill from Caltech called “Quantum Supremacy”. With this expression, they want to highlight the superiority of quantum computers with respect to classical computers. While the scientific achievement of the Google team is indeed impressive and to be lauded as an experimental milestone, I personally despise the notion “supremacy” because this also connotes “white supremacists” or racists and the like. Moreover, it insinuates that there is no other technology, which might be more “supreme”. Therefore, I advise you and my colleagues not to use this terminology and rather use “Quantum Advantage” because that is precisely, what we are getting. And the potential capabilities of quantum technologies have not even been fathomed as of today.

In their experiment, the Google team have indeed implemented a computation, which would last much longer on a classical computer; therefore, it certainly represents a milestone result. On the other hand, the algorithm, which they implemented, is an artificially complicated sequence of random circuits and not useful for anything besides showing that a quantum device can indeed achieve an advantage beyond classical computation. Therefore, this represents an important stepping-stone for future number crunching with quantum devices.

The importance of quantum technologies has also been realized (finally…) by European politicians and the European Union has established a so-called Quantum Technology Flagship, which started in the fall of 2018 with a ten-year program and an investment of 1 Billion Euros until 2028. By now, the first phase of the flagship program is on its way, pursuing the four pillars, which I have mentioned: Quantum Communication, Quantum Metrology, Quantum Simulation and Quantum Computation. However, bear in mind that this is an investment to bring the quantum technologies, which exist currently mostly in academic institutions to industry and to make them available for society. Basic research, as we traditionally know it, needs some additional funding from the member states. Europe is already lagging behind; we need to promote further, what we can do in our academic institutions. Much, if not a majority of the basic research in quantum technologies originated from Europe. Let us try to continue using the quantum world for humankind.

In this context, the universities in Europe and worldwide will have to undergo a change in their physics education. Physics as the ultimate basic research area, is often seen as the opposite to engineering, which is appreciated as an applied science. Therefore, we educate primarily physicists who know very little about engineering, and we have engineers who have no clue about quantum physics. This needs to be changed and some universities are already implementing curricula under the heading "quantum engineering" trying to combine the best of both worlds to pave the way for a widespread use and application of the quantum sciences as quantum technologies. The 18th century was the century of mechanics, the 19th century one of thermodynamics, and the 20th century was the one of electrodynamics and computer science. I expect that the 21st century will be the century of quantum mechanics and quantum technologies.

The Universidad Complutense has had a strong participation in these efforts, so let us continue in our endeavors to bring the quantum world closer to our classical world, in order to understand better, how the classical world emerges from the quantum world. It is a fantastic journey, let us join forces and let us employ quantum features for a better world.

Thank you so much for this great honor and all the best for a great quantum future.