Claude Cohen-Tannoudji

I was born on April 1, 1933 in Constantine, Algeria, which was then part of France. My family, originally from Tangier, settled in Tunisia and then in Algeria in the 16th century after having fled Spain during the Inquisition. In fact, our name, Cohen-Tannoudji, means simply the Cohen family from Tangiers. The Algerian Jews obtained the French citizenship in 1870 after Algeria became a French colony in 1830.

My parents lived a modest life and their main concern was the education of their children. My father was a self-taught man but had a great intellectual curiosity, not only for biblical and talmudic texts, but also for philosophy, psychoanalysis and history. He passed on to me his taste for studies, for discussion, for debate, and he taught me what I regard as being the fundamental features of the Jewish tradition – studying, learning and sharing knowledge with others.

As a child, I was very lucky to escape the tragic events which marked this century. The arrival of the Americans in Algeria, in November of 1942, saved us from the nazi persecutions that were spreading throughout Europe at the time. I completed my primary and secondary school education in Algiers. And I was also lucky enough to finish high school in very good conditions and to leave Algiers for Paris, in 1953, before the war in Algeria and the stormy period that preceded the independence.

I came to Paris because I was admitted to the Ecole Normale Supérieure. This French "grande école", founded during the French Revolution about 200 years ago, selects the top high school students who do well in the selective final examination. The four years at this school, from 1953 to 1957, were indeed a unique experience for me. During the first year, I attended a series of fascinating lectures in mathematics given by Henri Cartan and Laurent Schwartz, in physics by Alfred Kastler. Initially, I was more interested in mathematics but Kastler's lectures were so stimulating, and his personality so attractive, that I ended up changing to physics.

In 1955, when I joined Kastler's group to do my "diploma" work, the group was very small. One of Kastler's first students, Jean Brossel, who had returned four years before from M.I.T. where he had done research work with Francis Bitter, was supervising the thesis work of Jacques Emile Blamont and Jacques Michel Winter.

We were a small group, but the enthusiasm for research was exceptional and we worked hard. Brossel and Kastler were in the lab nearly day and night, even on weekends. We had endless discussions on how to interpret our experimental results. At the time, the equipment was rather poor and we did what we could without computers, recorders and signal averagers. We measured resonance curves point by point with a galvanometer, each curve five times, and then averaged by hand. We were, somehow, able to get nice curves and exciting results. I think that what I learned during that period was essential for my subsequent research work and key personalities such as Alfred Kastler and Jean Brossel certainly had a significant role in it.

We were going together, once a week, to attend the new lectures given in Saclay by Albert Messiah on quantum mechanics, by Anatole Abragam on NMR and by Claude Bloch on nuclear physics. I can still remember the stimulating atmosphere of these lectures.

During the summer of 1955, I also spent two months at the famous Les Houches summer school in the Alps. This school has contributed largely to the development of theoretical physics in France. At that time, the school offered an intense training in modern physics with about six lectures a day, for two months, and the lecturers were J. Schwinger, N. Ramsey, G. Uhlenbeck, W. Pauli, A. Abragam, A. Messiah, C. Bloch … to mention a few.

After finishing my "diploma" studies, I still had to get through the final examination "Agrégation" before leaving Ecole Normale as a student. The "Agrégation" is a competitive examination for teaching posts in high schools. The preparation consists of theoretical and experimental courses as well as some pedagogical training. You give a lecture attended by other students and a professor and after, there is a moment of general debate and constructive criticism in view of perfecting your lecture. Kastler, I remember, participated in the pedagogical training and he taught us how to organize and present our lecture.

Well, about this time I met Jacqueline who became my wife in 1958. She has shared with me all the difficult and happy times of life. She has been able to pursue her own career as a high school physics and chemistry teacher, to raise our three children Alain, Joëlle and Michel, to be part of the daily life of a researcher which can sometimes be very difficult and demanding. We have had, as many, our share of family tragedy and losing our oldest son Alain was a great misfortune to us all. Alain died in 1993, of a long illness, at the age of 34.

After the "Agrégation", I left the Ecole Normale and did my military service which was very long (28 months) because of the Algeria war. I was, though, assigned part of the time to a scientific department supervised by Jacques Emile Blamont. We were studying the upper atmosphere with rockets releasing sodium clouds at the sunset. By looking at the fluorescence light reemitted by the sodium atoms excited by the sunlight, it was possible to measure the variations with the altitude of various parameters such as the wind velocity or the temperature.

Then, in the beginning of 1960, I came back to the laboratory to do a Ph.D. under the supervision of Alfred Kastler and Jean Brossel with a research post at the CNRS (French National Center for Scientific Research). The lab had by then been expanded. Bernard Cagnac was finishing his thesis on the optical pumping of the odd isotopes of mercury and I was trying, with Jean-Pierre Barrat, to derive a master equation for the optical pumping cycle and to understand the physics of the off-diagonal elements of the density matrix (the so-called atomic "coherences"). Our calculations predicted the existence of "light shifts" for the various Zeeman sublevels, a curious phenomenon we did not expect at all. I decided to try to see this effect. Cagnac left me his experimental set up during Christmas vacations and I remember getting the first experimental evidence on Christmas Eve of 1960. I was very excited and both Kastler and Brossel were very happy indeed. Kastler called the effect the "Lamp shift", since it is produced by the light coming from a discharge lamp. Nowadays, it is called light shift or a.c. Stark shift. I built a new experimental set up to check in detail several other predictions of our calculations, especially the conservation of Zeeman coherences during the optical pumping cycle. I submitted my Ph.D. in December of 1962. The members of the committee were Jean Brossel, Pierre Jacquinot, Alfred Kastler and Jacques Yvon.

Shortly after my Ph.D. Alfred Kastler urged me to accept a teaching position at the University of Paris. I followed his advice and started to teach at the undergraduate level. At about this time, there was a new reform in the University system: the so-called "troisième cycle" that consisted of teaching a graduate level with a flexible program. Jean Brossel asked me to teach quantum mechanics. He was teaching atomic physics, Alfred Kastler and Jacques Yvon statistical physics, Pierre Aigrain and Pierre-Gilles de Gennes solid state physics.

We had the best students of the Ecole Normale attending these lectures, so I set up a small group where every year a new student would join in and do a post-graduate thesis or a Ph.D. In 1967, I was asked to teach quantum mechanics at a lower level (second cycle). The book "Quantum Mechanics" originated from this teaching experience and was done in collaboration with Franck Laloë and Bernard Diu.

Understanding atom-photon interactions in the high intensity limit where perturbative treatments are no longer valid was one of the main goals of our research group. This led us to develop a new approach to these problems where one considers the "atom + photons" system as a global isolated system described by a time-independent Hamiltonian having true energy levels. We called such a system the "dressed atom". Although the quantum description of the electromagnetic field used in such an approach is not essential to interpret most physical effects encountered in atomic physics, it turned out that the dressed atom approach was very useful in providing new physical insights into atom-photon interactions. New physical effects, which were difficult to predict by standard semiclassical methods, were appearing clearly in the energy diagram of the dressed atom when examining how this energy diagram changes when the number of photons increases. We first introduced the dressed atom approach in the radio-frequency range while Nicole Polonsky, Serge Haroche, Jacques Dupont-Roc, Claire Landré, Gilbert Grynberg, Maryvonne Ledourneuf, Claude Fabre were working on their thesis. One of the new effects which were predicted and observed was the modification, and even the cancellation of the Landé factor of an atomic level by interaction with an intense, high frequency radio-frequency field. This effect presents some analogy with the *g*-2 anomaly of the electron spin except that it has the opposite sign: the*g*-factor of the atomic level is reduced by virtual absorption and reemission of RF photons whereas the factor of the electron spin is enhanced by radiative corrections.

We devoted a lot of efforts to the interpretation of this change of sign and this led us, years later (with Jacques Dupont-Roc and Jean Dalibard), to propose new physical pictures involving the respective contributions of vacuum fluctuations and radiation reaction. And while this was going on, we had some very stimulating discussions with Victor Weisskopf who has always been interested in the physical interpretation of the *g*-2 anomaly.

The dressed atom approach has also been very useful in the optical domain. Spontaneous emission plays an important role as a damping mechanism and as a source of fluorescence photons. Serge Reynaud and I applied this approach to the interpretation of resonance fluorescence in intense resonant laser beams. New physical pictures were given for the Mollow triplet and for the absorption spectrum of a weak probe beam, with the prediction and the observation of new Doppler free lines resulting from a compensation of the Doppler effect by velocity dependent light shifts. The picture of the dressed atom radiative cascade also provided new insights into photon correlations and photon antibunching. New types of time correlations between the photons emitted in the two sidebands of the Mollow triplet were predicted in this way and observed experimentally at the Institut d'Optique in Orsay, in collaboration with Alain Aspect.

An important event in my scientific life has been my appointment as a Professor at the Collège de France in 1973. The Collège de France is a very special institution created in 1530, by King François I, to counterbalance the influence of the Sorbonne which was, at that time, too scholastic and where only latin and theology were taught. The first appointed by the King were 3 lecturers in Hebrew, 2 in Greek and 1 in Mathematics. This institution survived all revolutions and remains, to this day, reputed for its flexibility. Today there are 52 professors in all subjects, and lectures are open to all, for there is no registration and no degrees given. We professors are free to choose the topics of our lectures. The only rule is that these lectures must change and deal with different topics every year, which is very difficult and demanding. It is, however, very stimulating because this urges one to broaden one's knowledge, to explore new fields and to challenge oneself. No doubt that without such an effort I would not have started many of the research lines that have been explored by my research group. I am very grateful to Anatole Abragam who is at the origin of my appointment at the Collège de France. Part of this teaching experience incited the two books on quantum electrodynamics and quantum optics written with Jacques Dupont-Roc and Gilbert Grynberg.

In the early 1980s, I chose to lecture on radiative forces, a field which was very new at that time. I was also trying with Serge Reynaud, Christian Tanguy and Jean Dalibard to apply the dressed atom approach to the interpretation of atomic motion in a laser wave. New ideas were emerging from such an analysis related to, in particular, the interpretation of the mean value, the flucalations and the velocity dependence of dipole forces in terms of spatial gradients of dressed state energies and of spontaneous transitions between these dressed states.

When in 1984 I was given the possibility to appoint someone to the position of Associate Director for my laboratory, at the Collège de France, I offered the post to Alain Aspect and then invited him to join me in forming, with Jean Dalibard, a new experimental group on laser cooling and trapping. A year later, Christophe Salomon who came back from a postdoctoral stay in JILA with Jan Hall, decided to join our group. This was a new very exciting scientific period for us. We began to investigate a new cooling mechanism suggested by the dressed atom approach and that resulted from correlations between the spatial modulations of the dressed state energies in a high intensity laser standing wave and the spatial modulations of the spontaneous rates between the dressed states. As a result of these correlations, the moving atom is running up potential hills more frequently than down. We first called such a scheme "stimulated blue molasses" because it appears for a blue detuning of the cooling lasers, contrary to what happens for Doppler molasses which require a red detuning. In fact, this new scheme was the first high intensity version of what is called now "Sisyphus cooling", a denomination that we introduced in 1986. We also observed, shortly after, the channeling of atoms at the nodes or antinodes of a standing wave. This was the first demonstration of laser confinement of neutral atoms in optical-wavelength-size regions.

A few years later, in 1988, when sub-Doppler temperatures were observed by Bill Phillips, who had been collaborating with us, we were prepared with our background in optical pumping, light shifts and dressed atoms, to find the explanation of such anomalous low temperatures. In fact, they were resulting from yet another (low intensity) version of Sisyphus cooling. Similar conclusions were reached by Steve Chu and his colleagues. At the same time, we were exploring, with Alain Aspect and Ennio Arimondo, the possibility of applying coherent population trapping to laser cooling. By making such a quantum interference effect velocity selective, we were able to demonstrate a new cooling scheme with no lower limit, which can notably cool atoms below the recoil limit corresponding to the recoil kinetic energy of an atom absorbing or emitting a single photon. These exciting developments opened the microKelvin and even the nanoKelvin range to laser cooling, and they allowed several new applications to be explored with success.

These applications will not be described here since they are the subject of the Nobel Lecture which follows this presentation. The purpose here was merely to give an idea of my scientific itinerary and to express my gratitude to all those who have helped me live such a great adventure: my family, my teachers, my students and my fellow colleagues all over the world.

I dedicate my Nobel Lecture to the memory of my son Alain.