Alfred Kastler: the Scientist and the Man*

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Fifty years ago, in October 1966, Alfred Kastler was awarded the Nobel Prize in Physics for the “discovery and development of optical methods for studying Hertzian resonances in atoms”. This citation sounds a bit exotic and I will explain below what it really means. I was then a young graduate student in the laboratory which Kastler and his former student Jean Brossel were heading in the Ecole Normale Supérieure (ENS) in Paris. I was working on my PhD, under the supervision of Claude Cohen-Tannoudji, who had himself been a student of Kastler and Brossel. I vividly remember how thrilled and proud I was to be in a research group whose work was recognized in such an exceptional way. Fifteen years before, Kastler and Brossel had founded their laboratory in the ENS Physics Department with the goal of developing methods to manipulate atoms with polarized light and radiofrequency fields. They had invented the “double resonance” and “optical pumping” methods which, by the early 1960’s, had matured into a very rich and fruitful domain of atomic physics. At the time of my PhD, the laboratory consisted of about twenty to thirty enthusiastic young scientists working around Kastler and Brossel, in an atmosphere of great freedom, trust and enthusiasm for basic science. Half a century later, I am still doing my research in this lab which, although it has expanded by about one order of magnitude over the years and diversified his research topics, continues to work under the idealistic values inherited from his founders. Being deeply indebted to

▲ Alfred Kastler was a man of science, but also a humanist and poet. He was also a recognized teacher who had a passion to convey. (<http://www.lkb.upmc.fr/50ansnobel/>)

Kastler and to his legacy, it is with pleasure that I have written this article which reminisces about Alfred Kastler, the scientist and the man.

Alfred Kastler was born in 1902 in Guebwiller, a small Alsatian town which was then part of the German Empire (Alsace had been annexed by Prussia following the 1870 Franco-Prussian war). Alfred’s mother tongue was German. He learned French as a foreign language in high school and did not speak it fluently when Alsace was reunited with France after the Great War. The young Alfred, who was a bright student, decided to study science, partly due to the influence of an exceptional physics teacher and partly because science did not depend upon the language it was formulated in. He attended in 1919-1920 a special class designed to improve the fluency of Alsatian students in French, then passed successfully the very competitive entrance examination to Ecole

저자약력

Serge Haroche 교수는 프랑스 물리학자로 양자 시스템을 파괴하지 않고도 양자의 개별 시스템을 측정 조작할 수 있는 획기적 실험방법의 업적을 인정받아 2012년 David J. Wineland와 함께 노벨물리학상을 공동 수상하였다. 1971년 파리6대학에서 물리학 박사학위를 취득하였고 1972년부터 1973년까지 미국 스탠퍼드대학교의 Arthur Schawlow 연구소에서 박사후과정 연구원을 거친 뒤 1975년 파리6대학 교수가 되었다. 2001년부터 Collège de France에서 교수로 재직하고 있으며 현재 서울대학교 석좌교수로도 재직 중이다.

Alfred Kastler 노벨상 수상 50주년을 기념하여 서울대학교 석좌교수로 계시는 Haroche 교수님의 기고를 심습니다. 원고를 집필하여 주신 Haroche 교수님과 더불어 도움을 주신 서울대 제원호 교수님과 전남대 노홍렬 교수님께 감사드립니다.

Normale Supérieure, whose classes he attended between 1921 and 1926. He got at ENS his education in physics under the guidance of Henri Abraham and Eugene Bloch, two physicists who were then heading the ENS physics department. Bloch advised Kastler to study quantum mechanics by reading directly in German the then newly published book of Arnold Sommerfeld "Atombau und Spektrallinien" (Atomic structure and spectral lines). It is through this reading that Kastler got acquainted with the angular momentum and magnetism of atoms, concepts which played later an essential role in his scientific discoveries.

While studying at Ecole Normale, Alfred married in 1924 a young history student, Elise Cosset, with whom he lived happily ever since. After graduating from ENS, he spent a couple of years as a high school teacher in Mulhouse and Colmar (two Alsatian towns), before joining the university of Bordeaux in the Southwest of France, as an Assistant Professor to prepare a doctorate in Physics (at that time, one could be the assistant of a Professor without having a PhD). His thesis, defended in 1936, dealt with the polarization properties of the fluorescence of mercury atoms excited in a step-wise process by light at two different frequencies. This experimental work led him to reflect about the principle of conservation of angular momentum between light and matter. He took seriously the theoretical idea, directly derived from Maxwell's equations and Einstein light quantum hypothesis, that circularly polarized photons carry one Planck constant unit of angular momentum along their propagation direction. He understood that this momentum was given to or removed from the atom when it absorbed or emitted circularly polarized light. The seminal idea which would lead to the double resonance and the optical pumping methods was already there in germ, but it took fifteen more years and important advances in another area of physics before it could come to fruition. For that, Kastler had to familiarize himself with magnetic resonance, another form of interaction of light with matter involving invisible radiofrequency photons instead of optical ones.

Isidor Rabi, who was to become much later a friend of Kastler, pioneered this new physics at Columbia University at about the time Kastler completed his PhD in Bordeaux. By submitting atomic beams to radiofrequency fields (so-called Hertzian radiation, as Kastler called it later) Rabi found that the atomic electronic or nuclear spins could be flipped,

leading to detectable signals when the atoms were passed through a gradient of magnetic fields separating the trajectories corresponding to different magnetic states. Here, as in Kastler's optical experiments, the resonance obeyed the principle of conservation of the angular momentum exchanged between the atoms and the invisible radiofrequency photons. The magnetic resonance concept was extended in 1945 by Felix Bloch and Edward Purcell, also in the US, to the phenomenon of nuclear magnetic resonance (NMR). They demonstrated that resonant angular momentum exchange could as well be induced in the nuclei of atoms and molecules in liquid and solid samples. The detection of the resonance was then achieved by directly detecting the radiofrequency radiation emitted by the nuclei through the induction signal it generated in an antenna loop. As we know, NMR became a very powerful method to investigate the properties of matter in physics, chemistry, biology and much later - through the MRI technique - in medical science. Rabi (in 1944) and Bloch and Purcell (in 1952) received the Physics Nobel Prize for their discoveries made just before and after the Second World War. This was a time when the French scientific community was isolated from the world of physics abroad. The NMR discovery had been greatly enabled by the development of the microwave technology which had been boosted by the research on the radar in England and in the USA. Research on these sources of radiation was classified for military reasons and its results were not immediately available to scientists like Kastler who spent the war years in Germany occupied Europe.

These have been very painful years for Kastler, as for most French people. He was then, in his late thirties and early forties, the husband of a high school teacher and the father of three young children. After getting his PhD in 1936, he had been appointed Associate Professor in Clermond-Ferrand in Central France, then back in Bordeaux where the war declaration caught him in 1939. As a man brought up between the German and French cultures, he was deeply troubled by the conflict between the two countries. His liberal mind was also shaken by the brutal ideology and inhumane behavior of Nazi Germany. Asked by the occupation authorities to participate as a scientist and a former German citizen to the war effort, he declined to do it. In 1941, he was called to Paris by Georges Bruhat, the head of the ENS Physics Department, in order to replace Pierre Auger, the famous physicist discoverer of

the auto-ionization phenomenon in atoms (the so called “Auger effect”) who had fled to America. At Ecole Normale, Kastler taught physics courses in optics and thermodynamics and pursued under harsh condition his research in atomic physics. During these dark years, he witnessed the deportation of the two mentors who had shaped his student years twenty years earlier. Eugene Bloch and Henri Abraham, who were Jewish, were sent to Auschwitz and killed by the Nazis. Georges Bruhat was also arrested by the Germans and died in deportation. After the war, Kastler helped to establish at ENS the “Three Physicists Prize”, awarded yearly to a French physicist in memory of the three scientists victims of the Nazis who have had such a strong influence on his scientific career.

The war had left the scientific life in Paris in complete isolation and disarray. After the Liberation, stunning news of scientific advances reached France. One was about the tremendous energy unleashed by the atomic bombs which devastated Hiroshima and Nagasaki. The military use of nuclear energy became a deep concern for Kastler, making him a pacifist and a strong anti-atomic bomb militant until the end of his life. The other great news was of course the discovery of NMR which was going to be essential for Kastler’s scientific work. Feeling intuitively that “Hertzian Spectroscopy” was going to be a new and powerful way to probe matter, he advised his young student, Jean Brossel, to go abroad in order to familiarize himself with the new atomic physics. Brossel went for three years to Manchester in England, then for three more years at MIT in Cambridge (USA), staying in touch by mail with Kastler in Paris. During this time, they forged a friendship and a scientific collaboration which led, after Brossel’s return to Paris in 1950, to the creation of the “Laboratoire de Spectroscopie Hertzienne” at ENS (later named Laboratoire Kastler Brossel) and to the discoveries of double resonance and optical pumping.

The principle of double resonance generalizes in a simple and elegant way the magnetic resonance phenomenon to atomic excited states. If an atom is transferred by absorbing a polarized optical photon to an excited state, it acquires the angular momentum of the photon. A resonant radiofrequency field can then flip this angular momentum, also called spin, resulting in the subsequent emission of a fluorescent photon when the atom comes back to its ground state. Since the radiofrequency has changed the atomic angular momentum ori-

entation, the polarization of the emitted photon is also modified. This change of polarization occurs only when the radiofrequency field has the right frequency to induce the spin flipping in the atomic excited state (this frequency depends upon the magnetic field applied to the atom). The phenomenon thus involves two resonant effects: an optical one (the absorption of the optical photon which excites the atom) and a “Hertzian” one (the absorption of the radiofrequency photon which flips the excited spin). Hence the “double resonance” name given to the effect. Predicted by Kastler and Brossel in their exchange of letters at the end of the 1940’s, the double resonance was observed in 1950 at MIT by Jean Brossel and Francis Bitter, the professor who was supervising his work there.

The scientific importance of double resonance was obvious. First, it allowed physicists to study magnetic resonance in excited states of matter, while NMR was generally restricted to ground states. The method moreover proved to be extremely sensitive, taking advantage of a huge amplification effect. The absorption of a very low energy radiofrequency photon was indeed detected through the emission of an optical photon carrying an energy several orders of magnitude larger. This optical photon was detected by a photomultiplier, with a high efficiency, while the detection of radiofrequencies in ground state NMR experiments had a very low quantum yield. Resonances in dilute atomic gases or atomic beams at room temperature and small magnetic fields became possible, while it was generally restricted in usual NMR experiments to dense liquid or solid samples at low temperatures and under high magnetic fields (in order to achieve at thermodynamic equilibrium a detectable magnetic level population change when the nuclear spins of matter were flipped). Most importantly, the discovery of double resonance led Kastler to the idea of optical pumping, a technique which exploits the interplay of optical and radiofrequency resonances to manipulate the ground states of atoms.

Kastler’s idea was simple and ingenious. Suppose you excite a paramagnetic atom (carrying a magnetic moment in its ground state) in a gaseous sample or in an atomic beam with circularly polarized photons propagating along the direction of a static magnetic field. It will then be brought to an excited state carrying the absorbed photon angular momentum. After a while (typically a few nanoseconds for usual atomic tran-

sitions), it will fall back to the ground state by spontaneously emitting a fluorescent photon. This photon may have the same polarization as the initially absorbed photon, in which case the atom will have its angular momentum finally unchanged. But the fluorescent photon may also have a polarization different from that of the exciting one. In that case, the final atomic angular momentum will have changed. Computing the odds for all photon emission outcomes, Kastler found that for many atomic species (especially alkali atoms and mercury which he had studied in his previous works), the average effect of an absorption-emission cycle could be a net transfer of angular momentum from the light field to the atom. Atomic electron spins (in the case of the alkalis) or nuclear spins (in the case of mercury) ought to be oriented along the applied magnetic field when the atom was illuminated by circularly polarized light. In the case of nuclear magnetism, the effect implied the interplay between the direct interaction of light with the atomic electrons and the coupling of these electrons to the nucleus via the so-called hyperfine interaction. Kastler thought that such an oriented state of matter at room temperature would be quite new, realizing a situation out of ordinary thermal equilibrium, which was bound to find fascinating applications.

To observe the effect, an important condition had to be fulfilled: the rate at which absorption emission cycles occurred had to be larger than the rate at which the atomic orientation got lost due to random collisions in the sample (a mechanism known as relaxation). This meant that the light intensity had to be large enough. Kastler noted that the atomic orientation could be detected by optical means, either by observing the change in the fluorescence light polarization, or by detecting the modification of the pumping light intensity which should decrease as the sample orientation augmented. Moreover, if a radiofrequency field was applied to the atoms, the orientation obtained through optical pumping cycles could be flipped, resulting in a change of the fluorescence or absorption features of the atoms. Thus, optical pumping could be used to detect magnetic resonance in atomic ground states, with a sensitivity comparable to that of double resonance, again exceeding by far that of usual NMR methods.

When Brossel came back from the US, he set up an experiment to observe the effect. It involved an atomic beam of sodium irradiated by the polarized light from a lamp filled with

sodium atoms excited by an electric discharge. The first optical pumping signal was observed in 1952 in an experiment with atoms flying during a couple of millisecond through the pumping light beam. The method was then extended to the orientation of gas samples pumped in sealed glass cells at room temperature. Brossel, a very clever experimentalist, became a master in the art of glass blowing, realizing cells coated with paraffin which minimized the relaxation of the atomic spins colliding with the cell walls. The characteristic optical pumping and relaxation times of alkali atoms increased from the millisecond to the second range, resulting in the observation of very narrow magnetic resonances having a line width of about one Hertz only. It then became possible to explore in details the magnetic properties of atomic ground states, to measure with high precision the magnetic moments of atomic nuclei and to study the subtle features of atomic relaxation processes (effect of interatomic collisions, of interaction with the cell walls and of the trapping of fluorescence photons undergoing multiple scattering inside the cell).

From the early 1950's to the mid 1960's, which was the time when I joined the "Laboratory of Hertzian spectroscopy", many breakthrough experiments demonstrating the power of the double resonance and optical pumping methods were performed by Kastler, Brossel and their students. Extension of the method to realize population differences between hyperfine levels in atomic ground state has been demonstrated. Transverse optical pumping in which the light beam feeds atomic angular momentum in a direction normal to an applied static magnetic field has led to the observation of new resonances whose interpretation required the concept of quantum interference. In these experiments, the pumping light is preparing quantum superposition of atomic states with various orientations of the atomic spin along the static magnetic field and the observed resonances are sensitive to the relative phase of the quantum probability amplitudes associated to the different states in the superposition. The light shift phenomenon is another important development of the early years of optical pumping. Claude Cohen-Tannoudji discovered during his PhD work that non-resonant light was shifting the energy levels of atoms, resulting in a small measurable shift of the magnetic resonance line of optically pumped atoms. Due to all these discoveries, the Kastler group rapidly became a world leading center of atomic physics, illustrating in a spec-

tacular way the rebirth of physics in France during the post-war years.

Many foreign scientists flocked in Paris to work in the Hertzian spectroscopy laboratory. One famous visitor was Charles Townes from Columbia University, the place where Rabi had started the magnetic resonance revolution. Townes had invented the Maser in 1954 (Maser is an acronym standing for “Microwave Amplification by Stimulated Emission of Radiation”). It was a molecular beam device which exploited the stimulated emission effect predicted by Einstein 40 years earlier in order to generate intense coherent radiation. The maser operated in the microwave domain and Townes was looking for ways to realize a similar device in the optical domain, which he tentatively called an “optical maser”. To operate it, a process realizing a population inversion between a ground and an excited state of an atomic transition was necessary. Townes wondered whether a generalization of the original optical pumping method could be used to achieve this goal in an atomic gas sample and this is why he spent several months in Paris in 1958, exchanging ideas with Kastler and Brossel. In the end, the first optical maser, which became much better known as the Laser, was invented in 1960 by Theodor Maiman. The population inversion required to achieve light amplification was realized by a flash light pumping a Ruby rod. This solid state device was very different from the gaseous one considered by Townes and the pumping process only remotely related to Kastler’s idea, but the general idea of using light to pump a system out of thermal equilibrium turned out to be decisive.

The invention of the laser gave a new impulse to optical pumping studies. Kastler witnessed some of these developments in the 1970’s and early 1980’s, and many more followed since. Replacing the classical optical pumping lamps by lasers producing much more intense and more monochromatic light made it possible to perform optical pumping experiments on a wide range of atomic species, pumping them more efficiently and improving the signal quality. Very sensitive magnetometer using as probes optically pumped paramagnetic atoms have been developed. Hyperfine optical pumping in the ground state of Caesium and Rubidium atoms has become a standard procedure in modern atomic clocks. In a medical application, optically pumped Helium or Xenon atoms inhaled by patients has been used to realize MRI imaging of their lungs, providing

information which complements that obtained by standard MRI procedures.

Beyond these direct applications, optical pumping has been a game changer in atomic physics studies, announcing other revolutions to come. The method invented by Kastler, based on the exchange of angular momentum between light and matter, has been the first example of manipulation of atomic states with light, allowing physicists to study atomic samples prepared in exotic, out of equilibrium situations, not usually encountered in Nature. Thirty years after Kastler’s invention, the advent of powerful tunable lasers has made it possible to exchange also the linear momentum between photons and matter, leading to the laser cooling and trapping of atoms. It is striking to note that laser cooling is based on photon absorption and spontaneous emission cycles similar to those that Kastler exploited in optical pumping. The light shifts experienced by atoms in non-resonant light beams, first observed in optical pumping experiments, play also an essential role in atom trapping and cooling procedures. Claude Cohen-Tannoudji got his Nobel Prize in 1997 (shared with Steven Chu and William Phillips) for understanding how light shifts, combined with optical pumping processes, provide extremely efficient laser cooling schemes bringing the temperature of atomic samples down to the micro-Kelvin range (the so-called Sisyphus cooling procedure). Further improvements based on evaporative cooling have allowed physicists to lower even more the temperature and achieve Bose Einstein condensation, opening the way to the study of novel quantum phases of matter with fascinating properties. Finally, the extreme sensitivity of optical detection methods based on optical pumping with lasers has made possible the manipulation and observation of single quantum particles, ions, atoms or photons. These experiments have been recognized by the Nobel Prize that I have been honored to share with David Wineland in 2012.

Kastler’s work and its legacy can clearly be recognized in the Nobel awards received by three members of the Kastler Brossel laboratory over the last half-century. A fourth scientist should have been added to this list. Jean Brossel has indeed played a major role in this scientific adventure. His experimental skills have completed Kastler’s imagination, making in my view this pair of exceptional scientists inseparable when it comes to attribute the merits of the optical pumping

discovery. Kastler agreed with that and he often said that he regretted not to have shared the Prize with his friend and colleague. Brossel never complained about it, which shows that he too was a real gentleman.

Kastler, who died in 1984, is remembered for many reasons beyond his achievements in physics. He was a concerned citizen of the world, interested in many issues beyond science. I already mentioned his dedication to peace and the control of nuclear weapons, which led him to be an active member of the Pugwash organization. He also intervened in various occasions to defend scientists persecuted in the world, in the former Soviet Union, or during the dictatorships in Argentina for instance. In France, he expressed his liberal ideas at a time when it required some courage. He took in the 1960's a strong position for the independence of Algeria. He did not hesitate during the 1968 student revolution in Paris to stand against the anarchist idea that elitism should be suppressed and that all students should be given a pass at their examination. Kastler was also a humanist. He used to write poetry in his native German tongue. He took a keen interest in philosophical ideas and in psychoanalysis. He was clearly a serious man, but he was not only that. He also had a strong sense of humor. He expressed it famously in a note he wrote for the proceedings of the French Academy of sciences. He had been elected in this famous institution at the age of 64, just before getting the Nobel Prize. Electing members passed their prime had become a worrying trend in the Academy. In his note, Kastler compared the evolution of the age of new members to that of the life expectancy over the last three century and he observed that the two curves were bound to cross each other, meaning that members would be at some point elected posthumously. This ironic remark led a couple of years later to a change in the Academy by-laws, which now make a provision to reserve a quorum of seats to young member

during each election cycle.

Let me conclude by some personal recollections. I was first exposed to Kastler's personality by attending his atomic physics classes as an undergraduate student. At that time, he was already a thin frail man, a little bent forward, with a slight dreamy smile. And he was a charismatic teacher. He had a special way to talk about atoms and photons in which the poetic side of his mind transpired. He used metaphors and analogies, giving to the atom a kind of strange reality which have left a lasting impression on me. Later on, I realized that he was a gentle and modest person, always ready to discuss with students and curious to learn from them. During my thesis work, he often came in my lab room to talk with Claude Cohen-Tannoudji and with me. He inquired about the progress of our research and asked pointed questions about subtle issues. Having learned quantum physics in his formative years at the time of the old theory of quanta, he was not at ease with the modern mathematical formalism. But he made up for this lack of familiarity by his imaginative mind, intuitively understanding the important points of a theory or an experiment. He felt until his late years the need to learn more about physics and one could find him often attending seminars or sitting in a physics or mathematics class room amid young students. His kind personality, open to others and always eager to expand his mind and his knowledge, has inspired me throughout the years, as it has inspired all the students and colleagues who have had the privilege to interact with him.

* I am indebted for details concerning Kastler's biography to Bernard Cagnac, one of the first students of Kastler and Brossel, now Emeritus Professor in Paris VI University. For French readers, I recommend Cagnac's book "Alfred Kastler, portrait d'un physicien engagé" (Alfred Kastler, portrait of a committed physicist), published by Editions Rue d'Ulm, Paris, 2013.