Essay: Fifty Years of Atomic, Molecular and Optical Physics in Physical Review Letters

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The fiftieth anniversary of *Physical Review Letters* is a good opportunity to review the extraordinary progress of atomic, molecular, and optical physics reported in this journal during the past half-century. As both a witness and an actor of this story, I recall personal experiences and reflect about the past, present, and possible future of my field of research.

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Physical Review Letters, founded in 1958 to publish rapidly the most important results obtained in all domains of physics, has been very successful in achieving this goal. The fiftieth anniversary of *Phys. Rev. Letters* is a good time to review the development of physics over the past half-century. Atomic physicists of my generation are inspired to reminisce about the important moments we have witnessed in our own field. In atomic, molecular, and optical physics (known as AMO physics), *Phys. Rev. Letters* has been the main journal in which new theoretical or experimental advances have been described for the first time. Leafing through its 300 000 pages—give or take a few—is a fascinating journey through a field that has renewed itself many times and has often made unexpected connections with other fields of physics.

In the 1960s, when both *Phys. Rev. Letters* and I were young, atomic physics was considered—at least by physicists working in other areas—as a mature field with a rather unpromising future. Recording atomic and molecular spectra with ever higher resolution was, after all, simply testing elementary systems whose basic properties were fundamentally known. Scientists in the field, though, knew better. Optical pumping methods were being developed as a way to manipulate atoms with light. One of the goals was to improve the resolution of spectroscopy—the traditional role of atomic physics—but it was far from being the only motivation. In fact, optics was undergoing a deep conceptual shift. Instead of being merely a probe of atomic spectra, light was becoming a tool to actively manipulate atoms, to

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force them to occupy some states out of the natural thermal equilibrium. Atomic physicists were increasingly fascinated by this challenge and the perspectives it opened.

At the same time, a new source of light, the laser, had appeared on the physics scene. Experimental physicists were learning about the laser's properties, getting it to work in various frequency ranges, operating it in continuous and pulsed modes, reaching higher and higher intensities, and investigating the nonlinear effects that occur when intense light is propagating through matter. A parallel effort was made by theorists to understand the properties of laser light, to describe its coherence, its classical aspects, and its inherently quantum features. Nobody knew at that time what the laser would be useful for in terms of practical applications. (It was said to be an answer to an unknown question.) Atomic physicists had nevertheless no doubt that it was going to revolutionize their research field. Lasers were bound to replace lamps in optical pumping studies, and the remarkable properties of laser light were opening up-to-then unforeseen opportunities to manipulate atomic states and to juggle with matter. Most of these developments have been reported in *Phys. Rev. Letters*, one notable exception being the first account of laser operation, which, so the story is told, did not pass the reviewing stage and had to be published in *Nature* in 1960 [1].

I got my first three papers describing optical pumping experiments published in *Phys. Rev. Letters* in 1969 and 1970, when I was still a graduate student. At that time, the journal had about 20 papers per issue, roughly 4 times fewer than nowadays. AMO physics, which has constantly made up between 5% and 7% of the total, was then represented on average by about one paper per week. I remember the exhilaration and the feeling of achievement each time I saw my name on the last page of the green-covered issue. It gave me the feeling of being part of a great international adventure, at a time when the contacts between scientists of different countries were far less numerous than today. Writing a *Phys. Rev. Letters* manuscript and following it through the various stages of publication were also quite different from what they are now. First, in the pre-word-processor era, we had to rely on the typing skills of a professional secretary, which compelled us to converge quickly and surely towards the final text. Bringing back a manuscript for retyping for the fifth or sixth time is a painful experience that I still remember vividly. I also recall the tedious word count to make sure that the paper would fit within the permitted boundaries, which were periodically redefined by complicated rules. It was—and still is—an interesting exercise in writing concisely for a Frenchman, consisting in replacing long sentences full of Gallicisms with the short and direct style characteristic of scientific English. (I am not so sure I quite succeeded in this exercise here.)

We also had to draft the figures by hand and to deal with a professional photographer to prepare clear pictures of oscilloscope images. In the 1961 Letter [2] reporting the first observation of laser light frequency doubling, the evidence was supposed to be a faint dot on a spectrographic plate picture, but, on the published figure, no dot was visible. The proverbial story is that one of the journal technicians had erased it, mistakenly believing it was a speck of dust. That was a warning to be careful and to prepare pictures impervious to such disastrous alterations. Once the manuscript was ready, it had to be dropped in a mailbox and trusted to the postal service. A long wait followed, before we got, about two weeks later, an acknowledgement notice from the journal's Brookhaven office that the manuscript had been received. The same delays occurred for each exchange with the referees. After publication, the paper embarked on a life of its own. Who and how many people read it remained a guess.

Contrast this with writing and publishing in our computer-assisted world. Using the *Phys. Rev. Letters* template, we can write the manuscript in the two-column format of the published journal and include ready-to-print figures directly processed from the experimental data. A mouse click instantaneously sends the paper to the editors and its fate through the refereeing process can be followed in real time on the American Physical Society web site. Before even being accepted, the paper can be downloaded by anyone on the electronic archive. As soon as it is published, the paper's success is directly measured by the number of citations it receives. There is no need to keep reprints anymore, since they can be retrieved, along with any other Letter, on the immediately accessible journal archives.

If the formal preparation of a Letter has become so much easier than 50 or 40 years ago, doing the hardware of physics—that is, getting the data—has become a much more complex and competitive affair. Even if AMO physics has remained small scale when compared with other fields such as particle physics or experimental astrophysics, it has become much more complicated and sophisticated than the field was then. A typical experiment was usually managed by a single student and typically involved a spectral lamp, one glass cell filled with a low-pressure gas, and a photomultiplier detector connected to a galvanometer or an oscilloscope. Now most experiments have tens of lasers operating together. Hundreds of optical elements have to be aligned on meter-long tables, forming a maze of laser beams intersecting with precision on atoms or molecules localized in traps or propagating in well-controlled atomic beams. Sophisticated cameras observe the atomic evolution, and fast computers are required to control complex procedures and to measure correlation signals that would have been absolutely impossible to track in the pre-computer era. Two or three students must work together to manage the various aspects of the experiment. They have to master a wide range of techniques, and I am always amazed how many skills they must acquire in a training time that—at least for French Ph.D. students—is much shorter than it was when I worked on my thesis.

The experimental complexity has allowed us to control matter at the atomic level with ever increasing sensitivity and precision. Such improvements have enabled AMO researchers to discover unexpected effects and to build bridges between atomic physics and other fields, including condensed-matter physics, nuclear physics, particle physics, astrophysics, and even chemistry. A few examples will underline some of the most spectacular developments of AMO physics in the past half-century. In a few words—and rather schematically—I say that about 10 orders of magnitude have been gained in the precision, sensitivity, temperature scales, and speed of the experiments. Developments of such magnitude involve not only quantitative but also qualitative changes in our knowledge of nature and our ability to control it.

Forty years ago, spectroscopy measurement results were given with six or seven digits at most. Some now include 17 significant figures. The precision is so outstanding that we can hope that looking for a tiny annual variation of atomic spectral lines will allow us to measure possible drifts of fundamental constants, which could yield deep insights into cosmology. Huge gains have also been made in the sensitivity of AMO experiments. One such example is that tiny polarization changes in light interacting with heavy atoms have demonstrated parity-violation effects in weak interactions. These effects, discovered 50 years ago in nuclear physics, were for a long time considered to be completely negligible in atoms. Their observation in low-energy processes is a very instructive—and very cheap—complement to data obtained from high-energy physics.

Whereas physicists in the 1960s were studying collective atomic samples made of billions of particles, they can now juggle with single atoms or control small samples made of a few atoms. Guided by clever proposals from theorists, AMO experimenters have engineered complex quantum states of such samples—ions in traps or atoms in optical potential wells—and studied how the information coded in their wave functions could be used for possible applications. Condensed-matter physicists, by producing artificial atoms out of quantum dots or superconducting circuits, have recently started to succeed in emulating atomic physicists in this game.

A similar gain in sensitivity has been achieved in the control of light. Most often in the 1960s, the light that was used as a tool for spectroscopy consisted of billions of photons and could be described classically. Experimentalists now play with single photons or with fields made of a small controlled number of light quanta. They are able to build and reconstruct states of light with intrinsic quantum properties, unexplainable in classical terms. The interaction of light with matter can be scrutinized at the single-atom–single-photon level, for instance, by trapping atoms and photons in small cavities. Combining the "quantumness" of light and matter in such experiments also leads to promising advances in the processing of quantum information.

About 10 orders of magnitude have also been gained on the temperature scale. Using radiation pressure and optical dipole forces, atoms that roam in gases at a few hundred meters per second are now routinely slowed down to velocities of a few millimeters per second. Translated into motional temperatures, these velocities correspond to a cooling from a few hundred kelvins down to microkelvins. The cold atoms can be trapped by gradients of magnetic fields forming a magnetic bottle, which store atoms with kinetic energies below a maximum value. As the height of the magnetic barrier is slowly lowered, the fastest atoms leave the bottle and the remaining gas rethermalizes via elastic atomic collisions at lower and lower temperatures. This so-called evaporative cooling process has allowed AMO physicists to reach the subnanokelvin domain and to achieve what are arguably the coldest objects in the Universe.

Ultracold atoms have de Broglie wavelengths in the micrometer range, and their dynamics can no longer be described classically. Studying such atomic waves has led to the discovery of new states of matter—Bose-Einstein condensates and degenerate Fermi gases. Trapping these systems in periodic potential wells made by intersecting light beams yields optical lattices in which atoms behave as electrons in metals, albeit at a quite different scale. Interactions between those atoms can be controlled by playing with optical parameters or with external magnetic fields. So-called Feshbach resonances, first encountered in nuclear physics, occur in the collisions between these cold atoms and can be used to generate cold molecules, opening the way to a new chemistry of ultracold matter.

The time resolution of AMO physics has also undergone the 10-orders-of-magnitude revolution. While processes occurring at the microsecond time scale were hard to follow in the 1960s, one can now take snapshots of ultrafast atomic processes, by illuminating atoms or molecules with laser pulses lasting only a fraction of an optical cycle, that is, a couple hundred attoseconds. Here again, chemistry is entering a new age, in which reactions can be followed in real time. As laser pulses are shortened, up goes their peak power. Maximum electric fields can reach values in the range of 10^{12} V/cm. Electrons exposed to such transient high-intensity fields are accelerated very close to the velocity of light, and ultrarelativistic effects occur in the interaction of light with matter. Acceleration of electrons in the wake of such intense field waves opens novel possibilities in particle physics.

All of these revolutions are related to each other. A detailed analysis of the connections between the hunts for precision, sensitivity, low temperatures, and ultrashort time resolution in AMO physics makes a very interesting story, which I can only briefly touch on here. Fighting the Doppler effect has played a major role in stimulating many research directions. In the 1970s, the development of tunable lasers offered spectroscopists an ideal tool for high resolution. They needed, though, to get rid of the line broadening due to the atomic motion. To get sharper spectral lines, they started by successfully developing nonlinear methods such as saturation or two-photon spectroscopy. They soon realized, however, that the best and most radical solution for eliminating the Doppler effect was to freeze the atomic motion altogether. That simple idea was the incentive to develop laser cooling and atomic traps, which in turn led to impressive improvements in the precision of atomic clocks. The optical frequency comb was developed to follow with high precision the ticking of those improved clocks, and this comb also turned out to be essential for the spectacular progress recently made in tailoring ultrashort light pulses.

What will a similar essay for the hundredth anniversary of *Phys. Rev. Letters* be likely to tell us about the development of AMO physics in the next 50 years? One thing is for sure. We cannot expect AMO physics to progress at the same pace as it did. Like Moore's law for computers, gaining a factor of 10 every five years in spectral resolution or temperature is bound to break down rather soon. Think, for instance, that atomic clocks are already sensitive to the redshift associated with a ten-centimeter altitude difference in Earth's gravitational field! AMO physics will still likely make substantial progress in its ability to control many-particle systems under simple conditions. That control will open the way to the simulation of complex systems encountered in condensed-matter physics, nuclear physics, and cosmology. One can hope that such simulations will lead to the understanding of still puzzling phenomena occurring in materials involving strongly interacting particles (such as high-T_c superconductivity).

The connections between AMO and other fields of physics are likely to strengthen further and to force future Ph.D. students not only to master several experimental skills but also to be knowledgeable in a broader range of theoretical topics in physics and chemistry. The future evolution of AMO physics will thus tend to counteract the worrying trend towards hyper-specialization that developed in physics during the past century. Beyond that, it is of course impossible to say where AMO—like the rest of physics—is going. I only wish that today's students, when reflecting in the year 2058 about their own careers, will consider themselves as privileged as I am for having taken part over half a century in the development of such a fascinating field of science.

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[1] T. H. Maiman, Nature (London) **187**, 493 (1960).
[2] P. A. Franken, A. E. Hills, C. W. Peters, and G. Weinreich, Phys. Rev. Lett. **7**, 118 (1961).