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Spectroscopy: present achievement and future prospects

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The state of spectroscopy is reviewed in the light of the discussions at this Meeting.

The papers at this Meeting have presented a broad perspective of spectroscopy, from the long traditions to the exciting present. Spectroscopy is a fascinating combination of very old and very new science. We still follow Newton in using prisms and Fraunhofer in using gratings. Nevertheless, as David D. Burgess said in *Nature* recently, spectroscopy has changed technically in the last 15 years more than at any time since Newton. In his words, it now almost constitutes a completely new subject.

To a considerable extent, the change in optical spectroscopy has been triggered by the availability of tunable lasers. But spectroscopy did not begin with lasers, nor does it end there. Interference spectrographs, most especially those using Fourier transform methods, are powerful complements to the laser methods. It is intriguing to think of what might be accomplished by combining a laser and a Fourier transform spectrograph, for instance in polarization labelling, to simplify complex spectra. Even in laser spectroscopy, many investigations require the utmost sensitivity in collecting light. There is much to be learned in that regard from the elegant techniques developed for astronomical spectroscopy.

In some ways, we have been rediscovering things from the past, and giving them new aspects. Nicolaas Bloembergen remarked in a recent discussion that really all we are doing in laser spectroscopy is adapting the things that were done in radiofrequency spectroscopy in the 1940s and 1950s. There is certainly an element of that, but optical spectroscopy differs because it is three-dimensional. We do make use of the directions of the beams and their diameters. Radio-frequency spectroscopy is essentially a point interaction because the size of the sample in, for example, nuclear resonance, is always very small in comparison with the wavelength. In microwave spectroscopy of gases we use a waveguide, and there is one direction along the waveguide, so that the experiments are essentially one-dimensional. Optical spectroscopy with lasers is three-dimensional, and some of the important possibilities that we know have come from recognizing that simple fact.

Although we now have a wide variety of lasers for spectroscopy, it is still sometimes impossible to find the right laser for a particular job. The tuning range of continuous-wave lasers does not extend very far into the ultraviolet, and is spotty in the infrared. We still have a rather limited choice of lasers suitable for spectroscopy. There is not yet an efficient continuous-wave laser in the visible region, and so we must use the inefficient and short-lived argon or krypton ion lasers to pump dye lasers. In the ion lasers, the discharge must run under very awkward conditions of high temperature and current density, which usually lead to erosion of the walls and contamination of the end windows. Replacement of an ion laser tube is a large and recurring expense. Nevertheless, ion lasers have made possible much beautiful spectroscopy in the visible and near-visible portions of the spectrum, and are indispensable tools for much of our research.

It seems especially difficult to make lasers with pulse lengths of a microsecond or so, although millisecond or nanosecond pulses are easily produced. A pulse of *ca.* 1 μs would be long enough for its brevity not to produce much spectral width. Thus a repetitively pulsed laser giving, say, 1 kW pulses of 1 μs duration would be powerful enough for many nonlinear effects like harmonic generation and mixing, but could still be monochromatic enough for high-resolution spectroscopy. Pulses of this length can be generated by flashlamp-pumped lasers, but it is difficult to make those lasers highly monochromatic because of heating of the dye during the flash.

Heating and excitation of the dye can cause subtle problems with pulsed laser amplifiers. Even if the input is a continuous-wave laser whose wavelength is known precisely, the output of the amplifier may well not be at quite the same frequency. As T. Hänsch & C. Wieman found in their investigation of the 1s—2s transition in hydrogen, when the amplifier dye solution is pumped, the refractive index changes, producing a change in the effective path length for the laser beam. This produces a shift in the frequency of the output beam, analogous to the Doppler shift from a moving mirror. Thus, for precise spectral measurements, the output wavelength must be measured.

One might still ask why we want to do spectroscopy. In 1970 I gave the Richtmyer Lecture to the American Association of Physics Teachers and the American Physical Society. Even though I could see only dimly the exciting era of tunable laser spectroscopy, which was then just dawning, I chose the title 'Is spectroscopy dead?' In preparation for the talk, I asked several colleagues if that title suggested any ideas. I expected that they might want to know what I meant by 'spectroscopy', because that could include such things as nuclear energy levels and mass spectroscopy. But Felix Bloch asked, 'What do you mean by dead?' Although the question was unexpected, the answer was easy. 'Turned over to the chemists', I replied. Indeed, that was what had already happened to both microwave gas spectroscopy and nuclear resonance spectroscopy. Bloch himself was once asked to give a talk about his discovery of nuclear induction, at Stanford's Chemistry Department Colloquium. 'Just tell us about the beginning', he was instructed. 'The rest we know much better than you.'

Chemists are surely going to have a continuing interest in spectroscopy for a long time, as they unravel the structure and interactions of molecules. Laser spectroscopy has shown the potential for an enormous increase in sensitivity of chemical analysis. Already, where they can be applied, laser spectroscopic methods are much more sensitive and selective than any other technique. For instance, a radioactive atom can disintegrate only once and then is lost, but many photons can be scattered from an atom without destroying it. It has been proposed that laser spectroscopic analysis might be the best way to detect the small number of atoms produced by neutrino interactions in liquids, and so to measure the low-energy solar neutrinos.

This same extraordinary sensitivity helps to make laser spectroscopy useful for a number of fundamental investigations on the frontiers of physics. It is being used to study rare atomic species obtainable only in very small quantities, such as short-lived radioactive isotopes produced in accelerators. It can also be used to observe very weak, nearly forbidden, transitions such as the 1s—2s two-photon transition in atomic hydrogen, which was used by Hänsch and his associates to measure the Lamb shift of the ground state of the atom. Very recently, Stephen Chu & Allen P. Mills, Jr have been able to measure the same transition in the simplest of all atoms, positronium. The positronium optical spectrum has until now remained almost unexplored because of the short life of that atom, which annihilates in less than a microsecond.

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Certainly we are now learning how to explore and measure these simple atoms far more deeply and precisely than ever before. The task of physics is not finished until we can understand matter in all its complexity. If physicists had confined their attention only to hydrogen atoms, they would not know about such fundamental concepts as exchange, let alone striking phenomena like ferromagnetism and superconductivity. Yet measurements of simple atoms permit sharp confrontation of our best theories with the actual behaviour of matter. We cannot be really sure whether these vastly improved measurements on simple atoms will again, as so often before, yield striking new insights into the nature of matter. The calculations are becoming increasingly complex, as theorists struggle to include all of the effects of nuclear structure, radiation recoil, and so on. Perhaps we shall only be able to test how good the latest computer programs are. But the chance of learning something really new is there as we continue to probe unexplored territory and to confront theory with more precise results. Another frontier is that of few-atom, few-photon interactions, which is becoming accessible with Rydberg atoms. So spectroscopy is very much alive for physicists.

Moreover, spectroscopy is likely to impinge on technology in a number of ways. The prospects for ultra-sensitive chemical analysis have already been mentioned. Moreover, spectral lines are the operating elements for lasers and other quantum electronic devices. If we are to get better lasers, we need to know what kinds of lines exist and how they can be excited. For that, we need to understand a wide range of atoms and molecules, for the simplest spectra are not always the most useful. Beyond that, we need to obtain a deeper understanding of how atoms and molecules can interact with radiation, both through steady-state conditions and under circumstances that lead to coherent quantum states. Experiments such as those on quantum beats and on Rydberg atoms in resonators can illuminate new aspects of the behaviour of matter and electromagnetic radiation, as well as providing new spectroscopic tools.

In short, spectroscopy is very much alive and will challenge scientists for a long time to come.

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