ing measurements will either force this limit lower or perhaps establish the existence of a nonlepton-conserving component.

Tests for time-reversal invariance in physical processes have been suggested in many areas of nuclear physics, and during the past decade several have been attempted. Perhaps the best known are those involving the electron–neutrino correlation in the decay of polarized neutrons, first studied by John Robson and collaborators in 1960, and those involving the phase difference between interfering electromagnetic multipoles in nuclear gamma-deëxcitation transitions. In the latter terms, time-reversal invariance implied phase differences of exactly 0 or 180 deg between the interfering multipoles. Until late 1967 the uncertainty in these phase differences was ±5 deg. In new measurements on Ru^{99}, however, Ottmar Kistner has shown that the phase difference (at least in this instance) between interfering M1 and E2 multipoles is 180 deg to within ±0.15 deg, establishing a much more stringent upper limit on the possible amplitude of time-reversal noninvariant components.

As a final example of use of the nucleus as a microscopic laboratory we consider the possibility of the long-term temporal variation of the protonic charge e. In 1937 P. A. M. Dirac suggested that e^2 might vary directly with cosmological time t. Recent detailed examination by Freeman Dyson of the beta decay of Re^{187} to Os^{187} has demonstrated that during the period since termination of nucleogenesis in our region, for instance 3×10^9 years, e^2 has remained constant by a factor of more than 300 beyond what the Dirac suggestion would have required. Further evidence against long-term variation of e^2 has been adduced by Asher Peres from the stability of heavy nuclei. Even a very small change in e^2 would shift the most stable $A = 238$ isobar from U^{238} to Pu^{238} or Cm^{238}. Nuclear physics is unique in providing temporal measures of adequate duration to examine such hypotheses.

CONCLUSIONS

Nuclear physics has reached a degree of maturity that permits the posing of sophisticated questions concerning nuclear structure and behavior. The broad outlines of the field are relatively known although surprises occur with refreshing regularity. Fortunately new techniques, both experimental and theoretical, have been developed that permit the search for answers to these questions. Many yet remain unanswered, and indeed each new development appears to open more new questions than close old ones; this is the mark of a healthy and on-going field.

Major new instrumentation has only recently become available in research centers around the world; the precision and quality of data obtainable with this instrumentation is roughly two orders of magnitude better than before. Major progress can be expected, as well as many surprises and new insights.

Only recently too has the function of the nucleus as a microscopic laboratory been exploited in fundamental physical studies; these will certainly increase in number and delicacy.

The soon-to-be-available very high-energy electron and proton accelerators designed for nuclear research will add a completely new facet to nuclear research and provide an array of probes transcending anything now available. Our attack on the nuclear many-body problem is well underway, but a long road yet remains for us to follow in the 20 years to come. □

TWENTY YEARS OF PHYSICS

ATOMS, MOLECULES AND ELECTRONS

By LEWIS M. BRANSCOMB

CAN WE EVEN REMEMBER atomic, molecular and electron physics 20 years ago? When fine-structure states of atomic hydrogen were still happily degenerate according to Dirac theory, and there was no conclusive demonstration to the contrary? When the dissociation energies of the simplest molecules such as nitrogen and carbon monoxide were unknown? When you could call an electron beam with 1-eV energy spread a "monoenergetic beam" and leave the audience smiling approvingly?

It would seem that only a few of us can claim a first-hand memory, because estimates show that this oldest field of "modern" physics has had remarkably rapid growth. The Novick subpanel (on atomic and molecular physics and quantum electronics) of George Pake's physics survey study found, in 1965, that the training in the US of new scientists in this field would double the numbers in three years if they all remained in the field. Estimates of the actual rate of international growth suggest a current doubling time of 3.5 years. *Physics Abstracts,* in its 1947 annual index, listed about 260 papers that appear to be covered by its current definition of "atomic and molecular physics." This figure represents about 7% of the total for that year. In 1967 I extrapolate 3780 papers in the field, or about 10% of the total.

What we didn't know

We knew 20 years ago how to write down the Hamiltonian for an atomic system, but we were essentially restricted to a central field or hydrogenic approximation. We knew negative ions existed, but only for atomic hydrogen did we know the binding energy. Hyperfine-structure studies had been made spectroscopically in the

1930's, but the full power of molecular-beam, microwave-cavity and double-resonance techniques was just beginning to be exploited. Astronomers stood only at the threshold of recognizing the enormous impact that atomic physics would have on astronomy. The electron magnetic moment still appeared to be well behaved; it would be two years before Martin Karplus and Norman Kroll would compute the fourth-order corrections in quantum electrodynamics and many years before theory and experiment satisfactorily closed with the monumental work of H. Richard Crane and his colleagues.

Electron microscopy was already a thriving field, but the full appreciation of electron diffraction and interference effects was only beginning. People in electron physics could still be found in arguments about "particle–wave duality," and elegant experiments were being designed to show that electron beams have coherence lengths just as optical beams do. Gottfried Möllenstedt and Ladislaus Marton were yet to produce interference fringes from separate beams of electrons, recombined in analogy to optical two-slit interference.

Plasma physics in those days was called "gas-discharge physics." People were still trying to learn about atomic physics from the construction of complex models for the conduction of electricity in gases. A few, like Otto Oldenberg at Harvard who often noted that "all the phenomena of gas discharges have been explained, but none have been predicted," were leading

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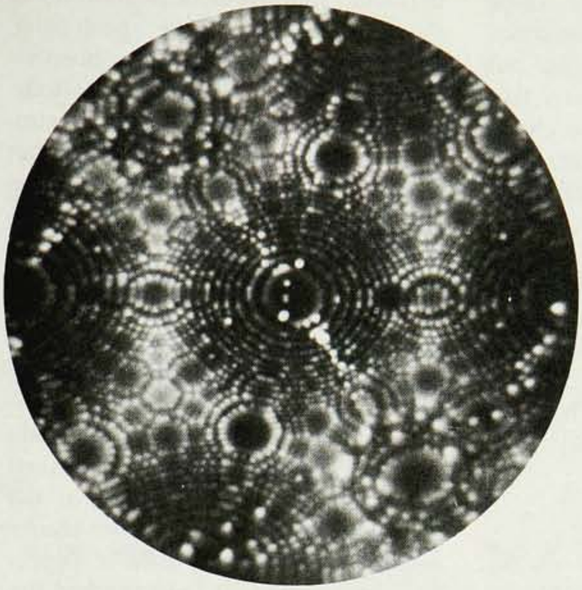


PLATINUM ATOMS (large spots near center) on a clean tungsten surface are seen in this field-ionization picture by E.W. Plummer and T.N. Rhodin. First photograph of this type was by Erwin Müller in 1957.

what was to become a major thrust of atomic-physics research: the design of complex and sophisticated experiments on the properties of isolated atomic systems. The results might be difficult to obtain, but they would admit of clear and unambiguous interpretation.

Atomic collisions. On the other side of the Atlantic, Sir Harrie Massey established the leading postwar school in studies of atomic collisions and their applications to astrophysics and aeronomy. Beginning with John Hasted's experiment on a staircase landing of the department of applied mathematics at University College London, Massey's group spun off David Bates's school of atomic physics in Belfast and had enormous impact on atomic physics in the US and elsewhere. V. M. Dukelskii and others in the Soviet Union were building another center of effort that would make impressive and unique contributions—especially in heavy-particle collisions and scattering theory—before the two decades ended.

In 1947 *Physics Abstracts* did not yet need a category called "electron field emission" or "mesic and muonic atoms and molecules" or "lasers" or "free radicals."

Recognition. Atomic and molecular physics was not, in 1948, really recognized as a field of physics. These areas had been in the 1920's and 1930's the vanguard of "modern" physics and were the proving ground for the development of quantum mechanics and radiation theory. But as the 1930's gave way to the holocaust of World War II, physicists in increasing numbers were pursuing higher energies and smaller dimensions. The new generation of atomic physicists divided after the war into groups, one attacking the remaining fundamental problems (especially those impacting on quantum electrodynamics), the others exploiting the great range of applications to which atomic physics lends itself. Atomic physics has shown that it is ubiquitous in its applications. In this sense also it has substantial fundamentality. Even though its logical foundations are thought to be secure, many exciting phenomena are being discovered, and it takes top-quality physics to unravel them.

In the past 20 years atomic physics has played a major role in the almost total conversion of astronomers to astrophysicists. The applications of electron-spin resonance to solid-state physics have been extensive. Nuclear spins and magnetic moments of unstable isotopes are largely derived from the molecular-beam work of this period. Almost all of our knowledge of ionospheric physics rests on the ion-chemistry and electron-collision data of atomic and molecular physicists.

Chemistry's debt. Perhaps the most important impact outside of physics itself has been in chemistry. Indeed, the Westheimer Report of the National Academy of Sciences Committee on Science and Public Policy describes in glowing terms the debt of chemistry to the techniques of physics and sees as chemistry's greatest opportunity the exploitation of these new tools. Even the illustrations showed the work not of chemists but of atomic physicists. It appears that a further revolution in physical chemistry is just around the corner, with chemists and atomic physicists working together towards a common goal. Both will benefit, as shown by a recent conference at the Joint Institute of Laboratory Astrophysics on the "chemical accelerator." But 20 years ago it was a rare thing to meet a scientist who could think both in "electron volts per atom" and "kilocalories per mole."

Activity and achievement

Let us consider just a few of the achievements of atomic and molecular physics in this 20-year period. The five mainstreams of activity that have been extraordinarily fruitful are electron physics, fundamental properties and precision measurement, quantum electronics, collision phenomena, and spectroscopy and structure. These five areas began from somewhat separate origins after World War II. Indeed, the lack of contact in the 1950's between physicists studying atomic collisions and those doing radiofrequency spectroscopy and optical pumping suggested that the Schrödinger equation had been divided up between two groups: one worrying about the angular parts of the wave function, the other concerned with its radial variation. The real success of atomic and molecular physics in the last five years has been the intellectual reunification of these separate paths. The International Conference on Atomic Physics to be held at New York University next month and the Sommerfeld Memorial Meeting in Munich next September symbolize this reunification.

Electron physics has produced magnificent work, some of which I have already mentioned. Perhaps the most spectacular is field-emission microscopy. On the basis of Erwin Müller's original work one can meaningfully state that individual atoms have been photographed nesting on a metal surface.

Properties and precision

In 1947 the fine-structure constant α was measured to an accuracy of only about four parts in 10^4 (from x-ray doublets), the electronic charge to 1 in 5000. Improvement in accuracy of the constants has been spectacular; now these uncertainties have been reduced by two orders of magnitude. We have from astrophysical spectroscopy a demonstration that α has not changed by more that two parts in 1000 in 2×10^9 years, and in the process can put an upper limit on the possible cosmological variation of the electronic charge with time. Molecular-beam techniques have given stringent limits to the possible electric dipole moment of the electron. Extremely sensitive tests have been made for a possible tiny difference between the magnitude of the charges of the proton and the electron. Both theory and experiment in the field of hyperfine-structure studies have reached the point where, for the hydrogen atom, the structure of the proton itself and fundamental questions of electrodynamics are at issue. Precision measurements of the hyperfine structure of muonium have been made. Another contribution of great fundamentality by Vernon Hughes and his colleagues is the search for anisotropy of inertia.

The atomic-beam radiofrequency-resonance apparatus has provided a frequency standard of great precision and long-term stability, with Norman Ramsey's hydrogen maser providing a frequency precision of better than one part in 10^{13}. Paralleling this tremendous improvement in rf measurements is the improvement in optical interferometry and the development of spectrally narrow light sources. In this period the rotation of the earth was discarded as a way of defining intervals of time; the second is now defined in terms of the hyperfine structure of cesium. We have also discarded the meter bar as our primary realization of the unit of length; the meter is defined in terms of the wavelength of a spectral line of krypton. And now we have in hand a great variety of sources of coherent optical radiation in the laser, which has produced its own revolution in precision length measurements not only over short distances but over distances of geophysical and even astronomical concern.

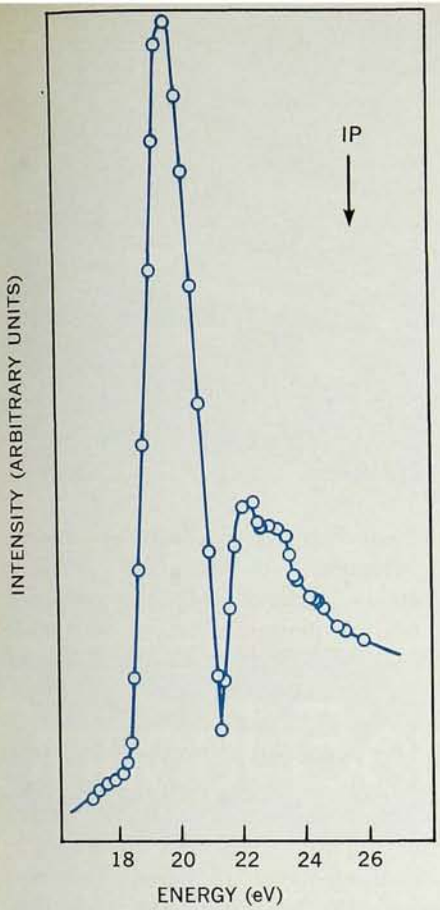
The laser is certainly one of the outstanding developments of the 20-year period. Its invention was the logical consequence of work in the radiofrequency region that began with the ammonia maser. It could have been invented accidentally much earlier. The fact that it was not supports the need to build a solid base of quantitative physical knowledge to aid the development of science. Indeed, if one looks in detail at the careful and logical approach taken by Ali Javan, Charles Townes and others in the study of atomic-physics information needed to make a working gas laser, one sees the value of the advances in basic atomic physics during these two decades.

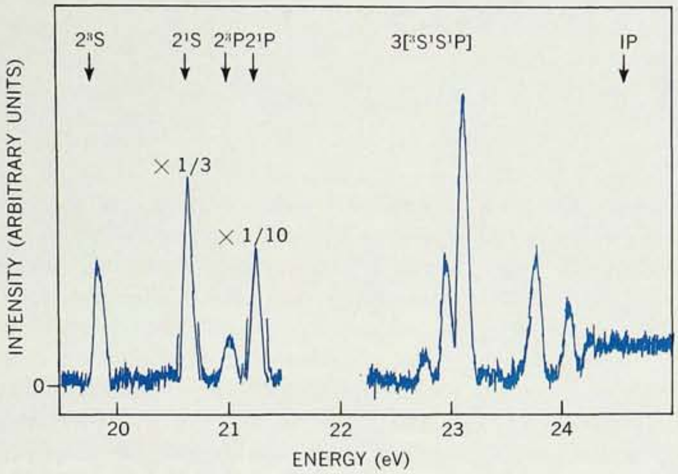
The full impact of the laser in atomic physics itself has not yet been felt. Pioneering studies of the nonlinear response of free atomic systems to intense optical radiation fields have been made by John Hall and others. In flux-density regions where the effects are still linear, the laser is a powerful tool for the testing of level structure, for angular distributions in photoionization and for the production of large populations in specific excited states for many purposes—for example, in molecular level-crossing experiments.

The laser has also made a great pedagogical contribution. In a sense it completes the circle started in the early part of the two decades with the electron-beam interference experiments and the Bohm–Aharonov effect. Soon the far infrared and submillimeter coherent sources (shall we call them "LASERS," "MASERS" or "IRASERS?") will fill in the gaps; the heterodyne techniques will be extended to higher frequencies, and "dial a line" will be a reality.

Collision phenomena

The most rapid advances in the study of atomic collisions were made early in the two decades, with the London and Belfast schools leading the way theoretically and Americans making the most rapid experimental advances. Crossed-beam techniques provided the means to study isolated atomic systems in clean, though complicated, experiments. Most important, atomic hydrogen could now be used as a target; the work of Wade Fite and his colleagues led the way. For the first time we could make a quantitative comparison between theory and experiment. In the second decade Michael Harrison's success in the crossed-beam measurement of the ionization cross section of the helium ion opened





IMPROVEMENT IN RESOLUTION yields more information in these electron-energy-loss spectra. Graphs show the energy lost by electrons to excitation in helium. Left: from N.F. Mott, H.S.W. Massey (1949). Right: J.A. Simpson et al 1965.

the way for crossed-charged-beams experiments. Finally a third achievement—the "confluent-beams" technique pioneered by Roy Neynaber and Erhard Rothe in the US and by Yu. N. Belyaev in Moscow—shows how beam energies that are practical in the laboratory can still permit study of interactions at center-of-mass energies in the range below 1 eV.

Electron physicists contributed an improvement of two orders of magnitude in the resolution of practical electron monochromators, and George Schulz's discovery of the "He⁻" resonance in the electron–helium differential elastic cross section opened the way for the exploration of resonant states in atomic scattering. Beam techniques have also been used for exploring the properties of negative ions, and of metastable states of many systems both long- and short-lived. A particularly interesting case is the long-lived ^4P states of lithium and of He^-, now well studied both theoretically and experimentally.

The field of ion-molecule reactions has also flourished. After the early years, when results on a few fragmentary cases might differ from one laboratory to another by orders of magnitude, we now see a regular production line of data of enormous value, particularly in atmospheric chemistry. The trend of work to come is seen in the experiments of William Chupka and Joseph Berkowitz, who study reaction kinetics with ions in specific initial rotational and vibrational states, combining the techniques of photoionization, crossed beams, mass spectroscopy and ion-molecule reactions.

Spectroscopy and structure

The nature of new advances is exemplified by the successful use of the electron synchrotron as a light source for the study of absorption spectra in the vacuum ultraviolet. The inner shell and multiple-excitation levels discovered by Robert Madden and interpreted by Ugo Fano tie the study of autoionizing states as approached from ultraviolet spectroscopy, electron inelastic scattering and x-ray spectra into a unit. No longer can physicists treat the atom as though the electrons, when perturbed, draw lots to see which one will respond while the others stay passively undisturbed.

Accompanying the experimental advances has been a great increase in sophistication of the theory. Group theory introduced great simplifications. The computer permitted a realistic inclusion of configuration interaction and wave distortion in structure and scattering calculations. *Ab initio* calculations for light atoms and simple molecules (especially hydrides) now begin to compete with, and even surpass, experimental accuracy. The accuracy of one-, two- and three-electron wavefunctions is now so great that Lamb shifts and other fundamental properties can now be computed for a variety of cases. Variational bounds on scattering lengths are available; perhaps we will have them soon for scattering phase shifts too.

The field has become reunified both intellectually and, in a sense, physically with the return of government and industry scientists to the campus. This major trend toward increased academic activity in atomic physics has expanded the training of younger people, who continue to find an unsatisfied demand in government and industry. Unity is also fostered by research groups and institutes devoted to a broad-based approach to atomic physics and its applications (for example, in laboratory astrophysics, chemical physics and plasma physics). The future of the field appears well assured by the continued infusion of interest and problems from other fields and by the resurgence of interest in atomic and molecular physics for its own sake. □