
Atomic physics: a renewed vitality

Benjamin Bederson

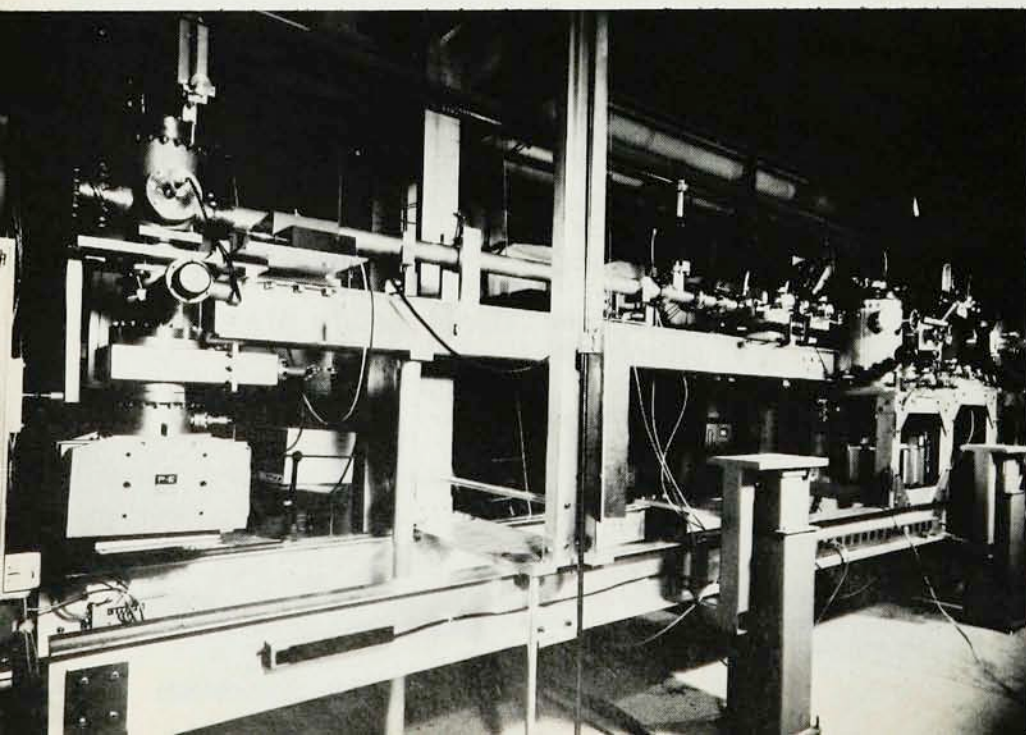


Benjamin Bederson is professor of physics at New York University and Editor of *Physical Review A*.

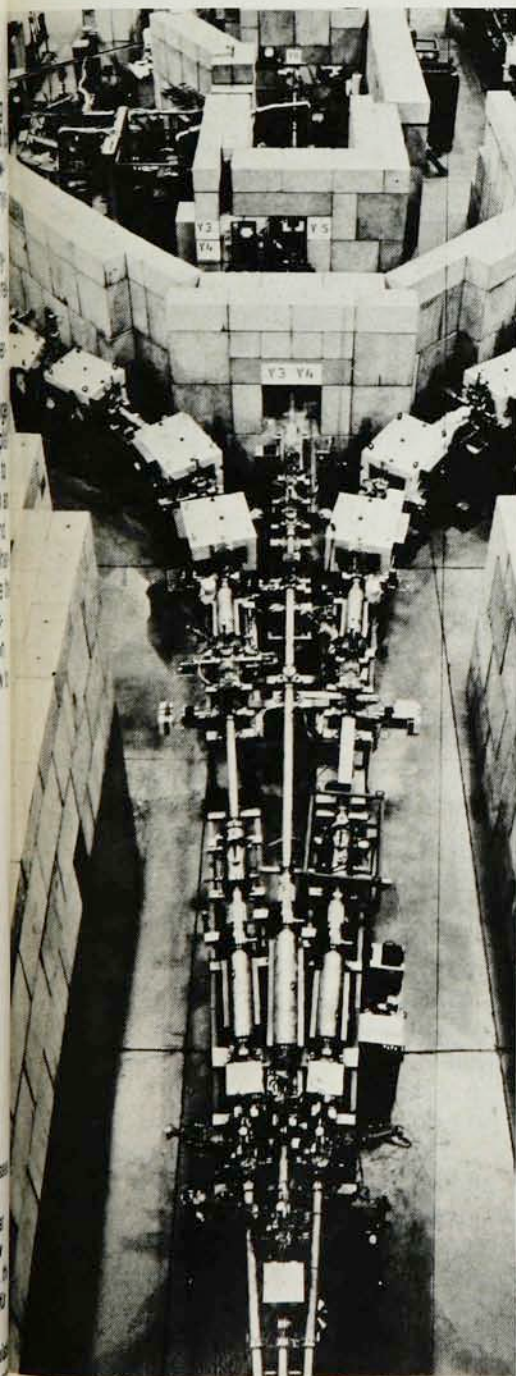
In 1951 I had just accepted a job as assistant professor at New York University. I was at the time a postdoc working in Jerrold Zacharias's atomic-beams laboratory at MIT. My PhD thesis (at NYU) had been in the field that was then called "gas discharges", and now has the more dignified appellation of gaseous electronics. I wondered what kind of experiment to set up, upon my return to NYU, that would effectively exploit my rather minimal expertise in two seemingly disparate fields, one involving complex macroscopic phenomena in the gas phase, the other an elegant, though technically challenging field that dealt with atoms one at a time.

On a visit to the late, lamented University Heights campus of NYU I encountered Edward Gerjuoy,

who was temporarily employed there that year. It was he who pointed out to me an interesting and little appreciated fact—that for one of the most elemental "few-body" interactions known to physics, namely the interaction of a free electron with an isolated hydrogen atom, there existed no reliable experimental information whatsoever! Lots of theory, perhaps, but not a single experiment. Having had this challenge offered up virtually on a silver platter it took no subtle reasoning to figure out how to perform such an experiment: cross electron and atomic hydrogen beams. Zacharias had taught me how to make the latter, using a Wood's tube discharge. John Pierce's book on electron beams taught me how to make the former.



Atomic beams apparatus. The crossed-beams machine at left was built by Bernardo Jaduszliwer and Bederson at New York University over the past few years (photo by J. Delgado). At right, the experimental hall at the Gesellschaft für Schwerionenforschung in Darmstadt illustrates the ultimate in currently available technology for high-energy atomic physics (photo courtesy of GSI Darmstadt).



It turned out that the Wood's tube was the wrong way to make a beam of atomic hydrogen, because of the large number of long-lived excited states generated by the discharge, and the cross sections I eventually measured were accordingly too high. But the experiment started me off on what was at the time an entirely new area of physics—the quantitative study of electronic and atomic collisions, using crossed beams.

One of the greatest experiments in atomic physics (or in any field, for that matter) of modern times had just been completed at Columbia—the Lamb-Retherford experiment, which directly observed the energy difference between the hydrogen $2^2S_{1/2}$ and $2^2P_{1/2, 3/2}$ levels: The experiment used radiofrequency fields to induce transitions from the metastable $2S$ state of atomic hydrogen to the non-metastable P levels. From the viewpoint of atomic physics this experiment broke all kinds of new ground (as well as the great implications it held for quantum electrodynamics). Like me, Lamb had first tried using a Wood's tube to obtain metastable atomic hydrogen in a single step involving both dissociation of H_2 and either excitation $1S \rightarrow 2S$ or cascade from higher states to $2S$. This method did not succeed, and he then employed a two-step method, first thermally dissociating H_2 in a hot oven, then bombarding the H beam produced in this oven with electrons. This may have been the first crossed-beam atomic-collisions experiment. Lamb and Retherford even presented a "re-

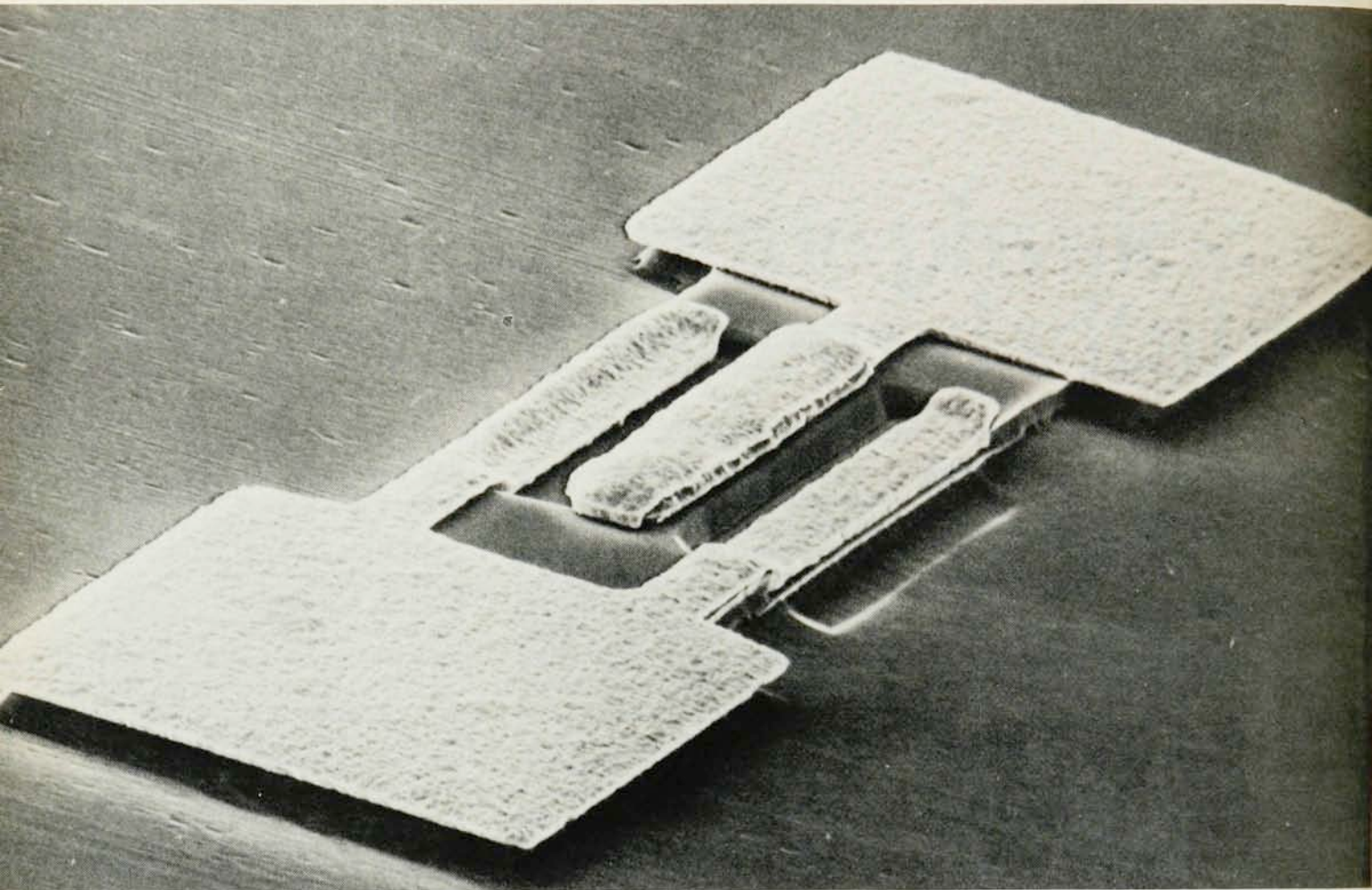
coil" analysis of the angular distribution of the excited hydrogen beam. Detection was by Auger emission of secondary electrons from a cold surface, a technique that was to be fruitfully employed in the many metastable scattering experiments that followed.

I was aware of the Lamb-Retherford experiment of course, but I did not fully appreciate what a seminal *atomic* physics experiment it was, because its motivation lay with quantum electrodynamics. And although I was perfectly happy to beg, borrow or steal all the experimental tricks of the magnetic-resonance beam trade, and these were considerable, I did not completely associate what could be called the "Rabi" school with *atomic* physics. In their work the atom was exploited as a probe to study the tiny influence of nuclear structure on atomic energy levels and thus measure static nuclear properties such as spin and magnetic and electric moments.

And I also did not know, at the time, that other young physicists were starting up experiments that had much in common with those at NYU. Wade Fite, coming from Otto Oldenberg's laboratory at Harvard was initiating electron-hydrogen crossed-beam collision experiments (with, incidentally, a thermal-dissociation source just like Lamb's), and Lewis Branscomb, from the same laboratory at Harvard, had started working on the formation and detachment of negative ions. Others were doing what could be called "heavy-particle" collisions, where both colli-



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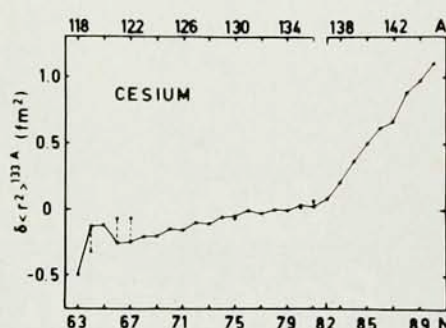
sion partners were atoms or ions: John Hasted at University College London, Nikolai Fedorenko at the Joffe Institute in Leningrad, Jap Kistemaker in Amsterdam, Sam Allison at the University of Chicago, Ronald Geballe at the University of Washington. Isadore Amdur was scattering helium off helium at "high" (that is, kilovolt) energies to probe the repulsive part of the interatomic potential, Edgar Everhardt at the University of Connecticut was doing pioneering work on high-energy rearrangement and ionization collisions, Richard Bernstein, a bit later at the University of Wisconsin (now at Columbia) started up elegant low-energy (that is, kT) collision studies between atomic systems to probe the attractive part of the interatomic potential.

It did not take long for me to learn that a thriving school of collision physicists had grown up during the 1930s in England, inspired mainly by Harrie Massey and his student David R. Bates, both now knighted. The theoretical tradition established by Massey and Bates resulted in a lasting strength of collision theory that led to a bumper crop of second-generation British theorists, including Michael Seaton, Alexander Dalgarno, and later, Philip Burke and Coulter McDowell. That tradition was transplanted to the US by the many Americans who traveled to University College and Belfast. That is not to say that there were no homegrown theorists—there were indeed, for example Gerjuoy, NYU's own Larry Spruch and, (if you want to call them home-

grown), Ugo Fano and Eugen Merzbacher.

I do not mean to imply that experimental collision physics did not exist before 1950. Starting with the Franck-Hertz experiment (the first observation of excitation by electron impact), very active collision groups had developed in Europe long before World War II, for example Ramsauer, Kollath, and Bruche in Germany, as well as R. B. Brode in the US, performing total electron-beam gas attenuation experiments. A number of excellent angular distribution electron-atom experiments were also performed, including some by Bullard and Massey. Many of these early experiments still hold up very well. All early experimental atomic collision work was summarized in the companion book to Nevill Mott and Harrie Massey's famous theoretical monograph *The Theory of Atomic Collisions* (first published in 1933), the definitive *Electronic and Ionic Impact Phenomena* by Massey and Eric Burhop.

While collision physics was experiencing its experimental rebirth, "Rabi" physics was beginning to move out in a variety of ways from its traditional nuclear emphasis. Vernon Hughes, a student of Rabi at Columbia, began to perform spectroscopy on so-called "exotic" atoms, the most extensively studied being muonium. This use of atomic-physics techniques to explore exotic systems (now including antimuonium and pionium) has established itself as one of the most fruitful areas for research on fundamental aspects of quantum electrodynamics related to



Variation of rms radius of cesium isotopes and isomers as a function of neutron number N and mass number A . [From R. Klapisch, in *Atomic Physics 7*, D. Kleppner and F.M. Pipkin, eds., Plenum, New York (1981), page 256.]



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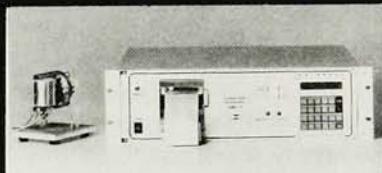
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atomic physics.

In 1968 Branscomb wrote an article for the 20th-anniversary issue of *PHYSICS TODAY* detailing the rapid growth of the field at the time. One of the highlights was a discussion of the extraordinary photograph (shown here on page 199) obtained by R. P. Madden and Kenneth Codling who used the NBS 180-MeV synchrotron as a broad-band source of ultraviolet radiation, showing a faint absorption line in the continuum absorption spectrum of helium. This was the $2s2p^1P_0$ doubly excited state which autoionizes into the singly-excited continuum spectrum. Ugo Fano explained its energy and line shape beautifully in terms of resonance-line profile theory. It represented a continuing characteristic of the "few-body" atomic physics problem, which is the close tracking of theory and experiment, with neither getting too far ahead (or behind) the other.

Another beautiful example was the first so-called "Feshbach" resonance in atomic collisions, seen by George Schulz in 1963 again in helium, just below the first excited state (long after similar resonances had been thoroughly explored in nuclear physics). Such resonances had originally appeared in computer calculations for electron scattering in atomic hydrogen, and Gerjuoy and others had suggested their possible existence in more complex atoms.

Why did it take so long to see these examples of quasibound states in atoms when they were commonplace phenomena in nuclear physics? The reason lay, I believe, in a matter of technology. The photoabsorption experiment had to wait until the venerable NBS synchrotron could be made available for atomic absorption work, and the electron resonance observations had to wait until nontrivial improvements in electron optics and monochromator design permitted them.

Still another variation of reso-

nance atomic physics appeared at about the same time—the enormously fruitful field of “optical pumping” in the gas phase. It originated in the famous Bitter-Brossel experiment, starting (as always!) as an elegant method for measuring nuclear magnetic moments, g -values and like—far simpler than beam techniques. These optical pumping methods eventually developed into a broad tool for studying atomic interactions, that is, line shapes, atomic g -values, and including the first measurement of a spin-exchange cross section, also helping set the stage for the maser and laser by making population inversions (called “negative temperatures” in the early fifties) seem natural and obtainable.

Books and Conferences

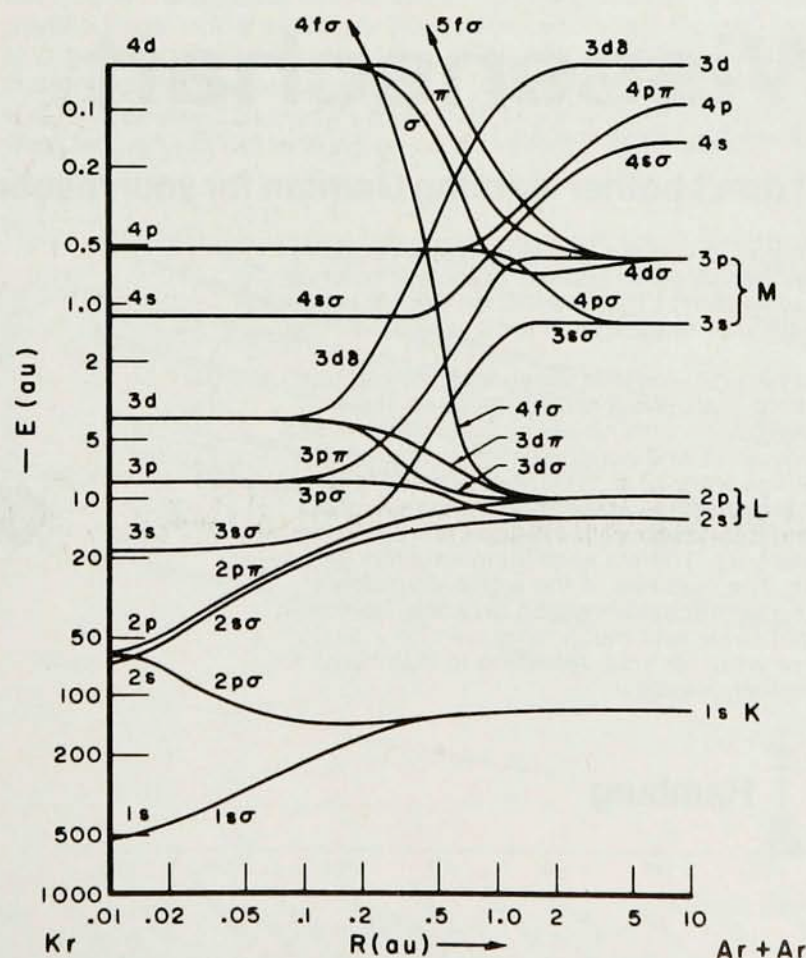
As happens frequently in physics, a field is often defined and its course governed by seminal books and conference series. I already mentioned the books by Massey and his coauthors Mott and Burhop—but there were other, equally important ones that kept the field going through its depression, and helped regenerate it when the time was ripe. In spectroscopy there was the masterful Condon and Shortley, *The Theory of Atomic Spectra*, and the primarily experimental *Resonance Radiation and Excited Atoms* by Mitchell and Zemansky. Condon and Shortley taught generations of budding atomic physicists about energy levels, vector-coupling schemes, atomic interactions with radiation fields and other subtleties, particularly of the angular parts of atomic wavefunctions. Mitchell and Zemansky's book (published in 1934!), was essentially the culmination of a quarter century of experimental spectroscopy; it was very modern in its outlook, and it helped educate experimenters to the equivalent subtleties of transition probability, Einstein A and B

coefficients, and even “negative absorption.” Many years after it was out of print, Mitchell and Zemansky continued to be used as a research source. Another masterful book that remains unsurpassed as a fount of information is Bethe and Salpeter's *Quantum Mechanics of One- and Two-Electron Atoms*, compulsory reading for any generation of PhD students working in atomic and molecular physics.

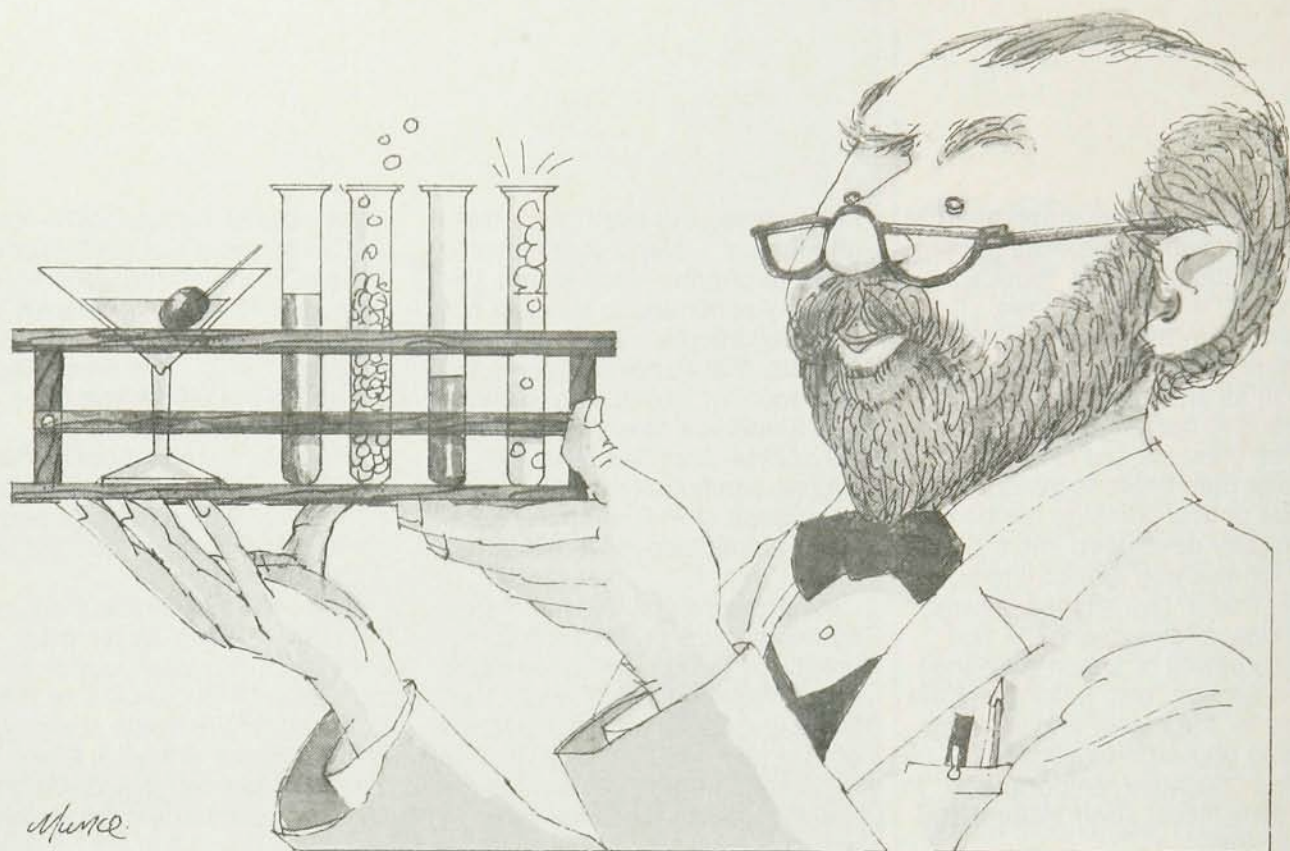
Along somewhat different lines, atomic physics has benefited greatly by the dedication of many scientists who have, through the years, published data compilations of exceptionally high quality. Perhaps most notable of these was the deceptively modestly-titled

three-volume *Circular 467—Atomic Energy Levels* of the National Bureau of Standards, otherwise known as “Charlotte Moore's Tables,” volume I of which was published in 1949. This was a successor to the earlier spectra compendium of Bacher and Goudsmit. In recent years this tradition has expanded to include, now, several data journals and atomic data centers (see the bibliography).

To complete this list, there is *Molecular Beams* by Norman Ramsey. This book, which appeared in 1956, remains to this day the primary single source of beam folklore, although it has been superseded in specific areas by more up-to-date monographs



Energies of molecular orbitals involved in fast collisions between argon atoms or ions. [From U. Fano and W. Lichten, *Phys. Rev. Letts.* **14**, 627 (1965).]



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and review articles. Unfortunately it is out of print, and accordingly old copies are greatly treasured by new generations of beamists.

Conferences have an equivalent effect on any growing field. For atomic physics two conference series have had a very important influence.

The first of these is ICAP (International Conference on Atomic Physics). While ICAP I was held as recently as 1970, its history goes back much further. In 1954, Victor W. Cohen—another of Rabi's students—organized what was called the "Brookhaven Molecular Beams Conference." It is of interest to examine the topics covered at that first beams conference. (See box on page 197.)

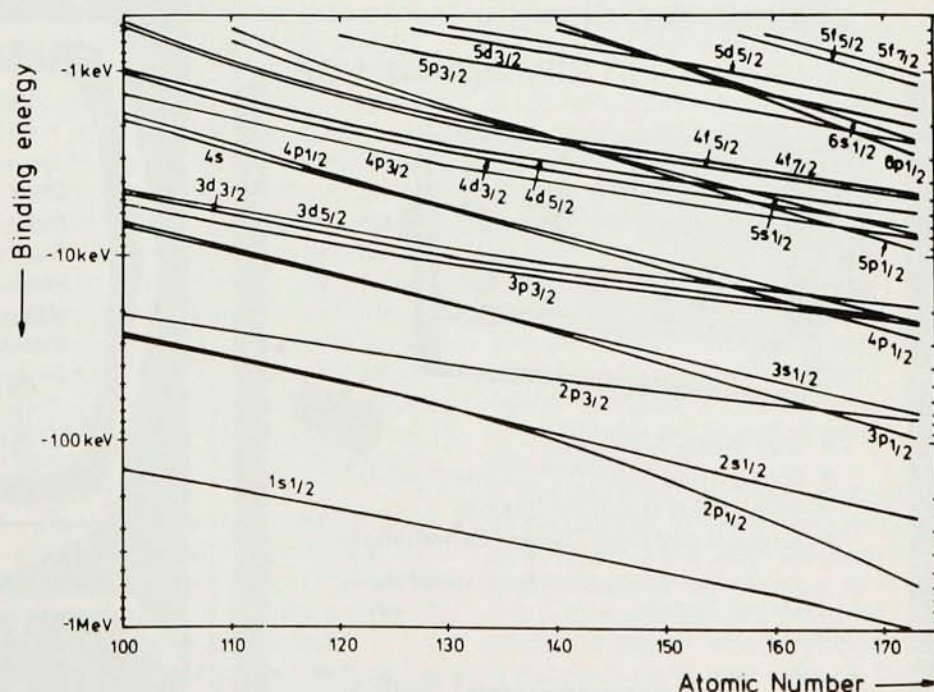
For years, Cohen kept these meetings going at Brookhaven, gradually expanding their scope, but basically maintaining their "magnetic resonance" character throughout. (Although, as one can see, even the call to the first conference included important talks not related to spins or hyperfine structure.) A significant step to broaden the Brookhaven Conference was taken in 1957, when it moved to Germany, where a combined meeting was held at Heidelberg and Bonn. To this memorable conference were invited, in full force, the European and American practitioners of resonance physics, including some with newer angles: W. Paul discussing his quadrupole mass spectrometer, for example. Later, Cohen began to round up support for a more general conference that would be appropriate to what was by 1969 a fully developed, thriving field. He enlisted, among others, Vernon Hughes, who with characteristic enthusiasm, proceeded to organize ICAP I. ICAP continues to thrive (ICAP VII is to

be held next summer in Göteborg, Sweden).

The other seminal conference series of modern atomic physics is ICPEAC, the International Conference on the Physics of Electronic and Atom Collisions.

In the early post-war days in the US, the Office of Naval Research was the principal source of funds for basic-physics research, including atomic physics. At NYU the ONR supported both Sidney Borowitz, in a theory grant, and myself. At some point in 1957, Sidney Reed, who was grants officer at ONR, dropped a casual suggestion to us. How would we like to organize a small international conference on atomic collisions at NYU? It seemed as though there were enough people working in

the field to warrant such a meeting. Intrigued by the idea, we agreed, and in 1958 the first ICPEAC was held at NYU. Perhaps 80 people showed up for this meeting, including many who, in later years, were to be leaders of the field, such as Jacob Kistemaker, who later helped found the FOM of Amsterdam (the Dutch laboratory for atomic and molecular physics that is now one of the most active centers for atomic and molecular physics in the world), Ron Geballe, and Branscomb, who later was instrumental in founding JILA—the Joint Institute for Laboratory Astrophysics at Boulder, Colorado—a brilliantly conceived and eminently successful joint creation of NBS and the University of Colorado. The Brit-



Inner atomic levels for atomic numbers between 100 and 173 from Dirac-Fock-Slater calculations. [From B. Fricke, in *Progress in Atomic Spectroscopy*, W. Hanle and H. Kleinpoppen, eds., Plenum, New York (1978), part A p. 190.]

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ish showed up in strength. Also present was one of the first contingents of Soviet scientists to attend a conference in the US, consisting of the distinguished pair of Lenin-grad physicists, V. M. Dukelskii, a noted theorist whose career spanned the revolution, and Nikolai V. Fedorenko. Fedorenko had established a heavy-particle collisions laboratory at the Joffe Institute. This laboratory is still a leader in the field, particularly as applied to studies related to magnetic-fusion plasmas. The most recent ICPEAC, number 12, held last July in Gatlinburg, Tennessee, had about 700 attendees and about 600 contributed papers.

Highlights

Singling out highlights for a 50-year period in any field is a tricky business. Even so, I believe it is possible to outline general areas in atomic and molecular physics where, one could say, the "action" has been most interesting, and offers particular promise of remaining so. (That this discussion to some extent reflects my own personal taste and prejudices goes without saying.)

Among these areas of general interest are ones that use high precision atomic spectroscopy in its various aspects, to perform ever more stringent tests of quantum electrodynamics and of parity and PT nonconservation in weak interactions, to measure precisely proton-electron charge differences, to engage in atomic quark hunts, to continue to test special and general relativity, and to make continually refined determinations of fundamental constraints. For these measurements the skill and ingenuity of the experimenters and equivalent computational mastery of the theorist are taxed to the extreme, because one is usually seeking to observe minuscule effects that could easily be overwhelmed by larger effects that are fully understood in principle, but not necessarily in practice.

Such work still includes measurements of the Lamb shift and $g - 2$ on one- and two-electron atoms, now also referring to highly ionized systems, almost fully stripped, or containing at most two electrons beyond closed shells. Also included are spectroscopic studies on muonium and pionium,

and the formerly exotic, now relatively commonplace, positronium.

On the same continuum, in terms of experimental techniques, but with somewhat different motivation, is the general area of "precision" atomic and molecular spectroscopy employed as a laboratory to study nuclear properties: this is the field that really started atomic beams and motivated the Brookhaven conference. A perfect illustration of this activity, still thriving, is the use of atomic spectroscopy to probe nuclear matter distributions by measurements of the hyperfine structure anomaly and the isotope shift. As tiny an effect on spectral levels as the addition of a single neutron to a high- Z isotope is still observable in either rf or precision optical spectroscopy (see the article by Olav Redi, *PHYSICS TODAY*, February, page 26).

For years Henry Stroke, at New York University, has been engaged in a systematic study of hyperfine structure anomalies, particularly on the stable and radioactive isotopes of mercury. Recently this undertaking has been revolutionized by the on-line mating of accelerator production of isotopes with magnetic-resonance and laser spectroscopic

techniques. By combining these techniques with mass selection in detection, one can work with radioisotopes having lifetimes down to the transit time across the beams machine (of the order of milliseconds). Determinations of nuclear spins, hyperfine structure and isotope shifts have been made, particularly at CERN, on, for example 27 (!) isotopes and several isomers of cesium, 20 of rubidium, and 22 of mercury. From such systematics one can obtain relative values for the effective differences of the nuclear charge radius $\delta\langle r^2 \rangle$. A plot of $\delta\langle r^2 \rangle$, relative to $A = 133$, for cesium is shown in the figure on page 191. The so-called "odd-even" staggering for the neutron-deficient lighter isotopes, and additional deformation for neutron-rich ones, are clearly seen.

But the interplay between nuclear and atomic physics has worked both ways—is the atom used as a probe to study the nucleus, or is the nucleus used as a probe to study the atomic wave functions? It depends upon who is doing the probing. Thus, for example, a measurement of the zero-field hyperfine splitting of a heavy atom—assuming the nuclear moments are known—represents a direct

July 6, 1954

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It appears as though the time is ripe for a conference and get-together on the general subject of "What is new in atomic beams"? You are cordially invited to attend such a conference at Brookhaven on Wednesday and Thursday, August 18th and 19th.

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- (1) Experiments with Excited Atomic States..... I. I. Rabi
- (2) Radial Magnetic Focusing and the Spin of Cu^{64} D.R. Hamilton
- (3) Radioactive Deposition and the Spins of Rb^{81} and Cs^{134m}
..... Berkeley, Argonne, and Brookhaven
- (4) The Theory of Nuclear Octupole Interactions..... C. Schwartz
- (5) Precision Experiments with Ga..... R. T. Daly
- (6) Multiple Quantum Transitions..... H. Salwen
- (7) Anomalies in Resonance Line Shapes..... H. Salwen

No doubt, there are numerous other developments which many of you have which have not yet been adequately described in the literature. Let us hear from you and we may get you on the program, either formally or informally.

Not having an active register of atomic beamists, we can write only to a few whom we can think of. A list is enclosed of those to whom invitations are being sent. If you know of any others particularly interested -- pass the word along and have them write to us.

We plan to start the morning of Wednesday, the Eighteenth, but suggest that to avoid the morning "Long Island Railroad Blues", you plan to come the evening before and enjoy the calm, restful atmosphere of Brookhaven.

You will be notified later regarding more detailed plans.

Very truly yours,

Victor W. Cohen
V.W. Cohen

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determination of the electronic wavefunction at the position of the nucleus.

From here one can move out to the spectroscopy of many-electron systems: the energy levels themselves, but also, lifetimes, oscillator strengths, and other static and dynamic properties of ground and excited states of few- and many-electron systems. These represent, of course, the observables of various moments of atomic wavefunctions: the many-body problem of time-independent quantum mechanics in its full glory, and all tricks and techniques of the many-body theorist are employed in this endeavor. From here it is but a small step to introduce the interaction of the many-body atomic system with radiation fields; and, of course, the entire history of quantum physics, not only atomic physics, is intimately interwoven with the story of this interaction.

The next step on this path to increasing complexity brings us to atomic collisions: the interaction of two atomic or molecular systems, or fragments thereof. Simply citing the more important possible reactions that could occur between such collision partners over various energy domains (from below thermal to GeV) could consume the remainder of this article. These would include, to name a few; elastic scattering, electronic (and rovibronic if molecules are involved) excitation, *inner-shell* excitations, charge transfer, rearrangement collisions, single and multiple ionization, attachment and detachment of negative ions, bremsstrahlung and radiation- (especially, now, laser-) induced collisions. A somewhat simpler collisional situation generally prevails if one of the partners is an electron or positron; I will return to this case later.

The field of heavy-particle collisions, like so much of atomic

physics, owes a great deal to nuclear physics, notably in the use of accelerators, but also in various source and detector techniques. In the US, I believe it was Sam Allison at the University of Chicago who first turned the nuclear arsenal onto high-energy atomic problems: He presented a paper entitled "Electron capture and loss in gases by helium ions in the kinetic-energy range 100–450 keV" at the first ICPEAC. The richness of this field is not an unmixed blessing, because unless source and target are carefully and wisely chosen, and unless detection is highly selective, there may be simply too much going on to permit a fruitful unscrambling. But, after all, physicists are careful and wise, and as a consequence there has been a veritable torrent of information that flows from such experiments. The ICPEAC Proceedings contain a healthy representation of heavy-particle collision work, and a very comprehensive report has just been prepared at a high energy atomic physics workshop, which describes recent activities in this field in general terms, and outlines some of its most interesting challenges (see the bibliography).

Not all heavy-particle interaction work is accelerator-related. At lower energies, the field blends smoothly into chemical physics, since beams techniques are a natural way to study chemical reactions.

It is really a hopeless task to attempt to represent the wealth of heavy-particle interaction in this short review. Perhaps a bit of the flavor can be gleaned from several interesting examples. One such is inner-shell electronic excitation. One of collision physics' early surprises was the unexpectedly large cross sections for such processes viewed (naively, in retrospect) from the viewpoint of adiabatic tracings of inter-nuclear potential

diagrams by the collision partners. The direct coulombic interaction to transfer nuclear kinetic energy to electronic excitation is too inefficient to account for these large cross sections. Rather, a characterization in terms of a "promotion" model, particularly near curve-crossings, can account for a wide variety of inner-shell processes.

The correlation diagram that is the basic for this viewpoint is illustrated on page 193 in a figure from a paper on Ar-Ar collisions by Fano and W. Lichten. At large internuclear separations one has simply the energy levels of the isolated argon atoms; at small separations (of order $0.01 a_0$), the almost united (krypton) atom. An important consequence of such curve-crossings, qualitatively explained by the promotion model are the radiative decays of inner-shell vacancies in high energy atom-atom collisions. The study of molecular orbital broad-band x-ray emissions, now a very active subfield of collision physics, was initiated in the modern era by F. W. Saris, W. F. vander Weg, H. Tawara and R. Laubert, [Phys. Rev. Lett. **28**, 717 (1972)], who observed a "noncharacteristic" x-ray band around 1 keV, when solid silicon was bombarded with argon atoms in the hundred keV energy region, attributable to the temporary united atom. [Actually x-ray production in bombardment of solid targets by mercury ions at MeV energies was observed, and even roughly explained, by W. M. Coates in 1934 (Phys. Rev. **46**, 542).]

Such work has now been extended to the most interesting area of united atoms whose combined atomic charge is sufficiently great to enter the domains of strongly relativistic and quantum electrodynamic effects.

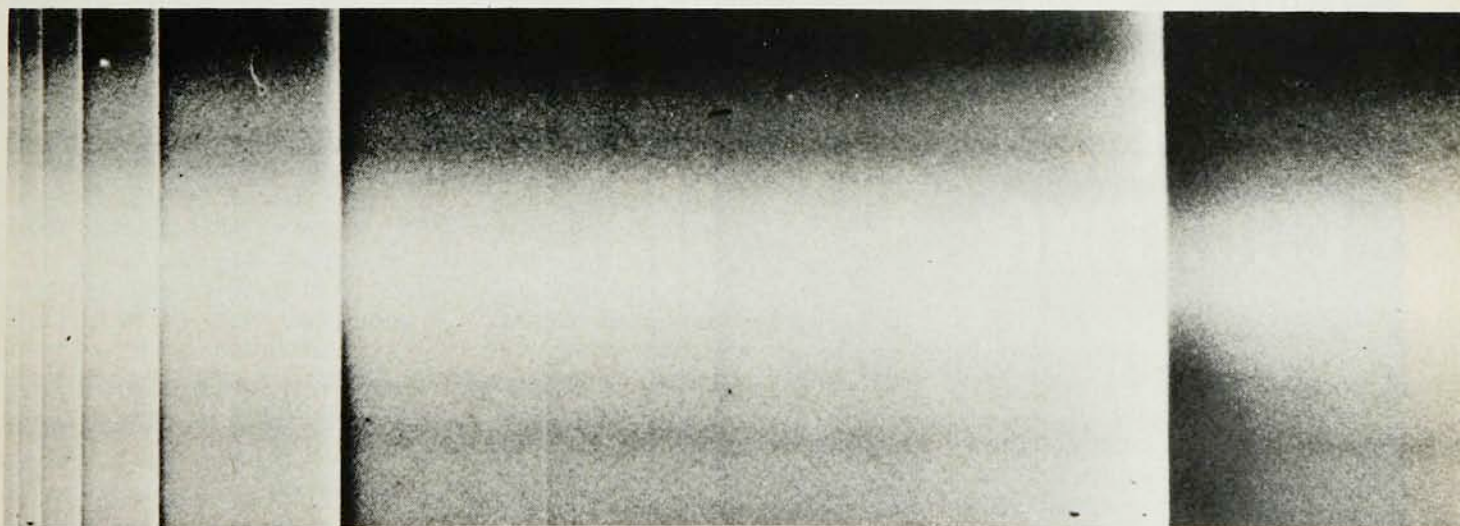
Nature has not been particularly

obliging in turning up long-lived nuclei with $Z > 105$. Alternatively, such "superheavies" can be studied during the time when two high- Z collision partners approach each other to distances of 10 fm or so (see the figure on page 195). Obviously we are not talking here about small accelerators in university basements, but instead to GeV machines such as the one at Darmstadt. For contrast I cannot resist, at this point, showing one figure (page 203) that also refers to heavy-atom collisions, this time at a thermal energy of, say, about $\frac{1}{10}$ eV. Here a state-selected molecule of HD collides with a Ne target and undergoes $0 \rightarrow 0$ and $0 \rightarrow 1$ rotational transitions (corresponding to an energy difference of the order of milli-electron volts) which are resolvable by time-of-flight discrimination.

Now let us return to the scattering of electrons by simple atoms. This subject has been a mother lode of collision physics since the earliest days of quantum mechanics, when Ramsauer first observed a deep minimum in the cross section while studying the transmission of low-energy electrons through the heavier rare gases.

Since that time, the close tracking of theory and experiment in this subject has continually led to significant and stimulating progress. The early "static potential" work of the theorists gradually expanded, as the very complicated methods required to include polarization, exchange and inelastic and continuum processes became more manageable. Formally, Massey had already properly formulated the $(n+1)$ body problem in terms of an expansion of the n -

body target basis set, including exchange. This became known as "close-coupling" in actual calculations because for practical reasons only a few such states could be employed in a manageable expansion: for such a few-state expansion, the coupling of the included states has to be close—compared to the contributions of the infinity of neglected states—to obtain convergence! Other approximations, spiritually related to close coupling but explicitly including such physically important effects as polarized orbitals, exchange approximations and optical potentials, followed. Spruch and his coworkers showed how to adopt nuclear "effective-range" theory to the more pathological atomic problem (pathological because the Coulomb interaction has such a long-range nature in com-



Anomalies in the absorption spectrum of helium due to doubly excited states. The prominent line at right is due to the $2s2p^1p_0$ state; it was barely visible in the original photo as published in *Phys. Rev. Letts.* [10, 516 (1963)]. This later photo shows several lines clearly. (Courtesy of R.P. Madden.)

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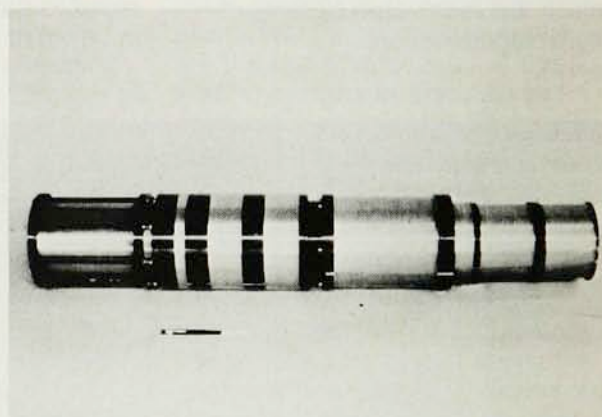
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parison to the nuclear interaction). More recently many-body theory along with very heavy computer usage has been successfully employed, pioneered originally by Robert Nesbet at IBM (San Jose) and others, and now practiced by many computationally skilled physicists and physical chemists.

It is interesting to note, however, that as close as this theory-experiment tracking has been, the common meeting ground has not been uniquely defined. The theorists compute what one might call a single identifiable process, or "channel," at a time. These include individual angular momentum and spin states of the $n + 1$ electron system, before and after the collision, for every allowed reaction channel at every polar and azimuthal scattering angle. To compare an ordinary scattering experiment with theory, one must perform many summations and integrations. One of the great challenges of experimental collision physics in recent years has been the quest to simplify these as much as is practically feasible by judiciously prepared collision partners in selected states (spin, angular momentum, fine or hyperfine energy) and by judiciously analyzing the products for state changes after the collisions, as a function of electron energy and angles. None of these tasks is trivial, but the vast bag of tricks developed over the years has enabled such experiments—with polarized atoms, polarized electrons, laser-prepared electronically excited atomic states, coincidences among electrons and phonons—to become more and more commonplace. We are, indeed, getting close to the so-called "perfect" scattering experiment, in which *all* possible observables in a given collision problem in the one-electron atom (an alkali or an atomic hydrogen atom) can be measured, either in a single experiment, or by combining several. The simplest example is in low-energy elastic

scattering of electrons by such one-electron atoms, where three independent measurements must be made as a function of energy and angle. This is because such scattering is completely characterized by two scattering amplitudes, coherently connected, (singlet and triplet, or, equivalently, direct and exchange), which in turn are completely specified by, say, two magnitudes and a relative phase (apart from one arbitrary absolute phase).

In the more complicated example of one-electron excitation, there are *four* required scattering amplitudes (two direct and two exchange, each referring to a component of the excited state orbital angular momentum, with $m = \pm 1$ being degenerate in the non-relativistic limit), and accordingly seven required observations. In fact a greater body of data on so-called alignment and coherence parameters for such excitation exists in the rare gases, particularly helium, than for one-electron systems. This, of course, is because experiments involving rare gases are generally easier than those involving alkalis or (especially) atomic hydrogen. An elegant formulation of the excitation of rare gases, applied to coincidence experiments, has been made by Fano and Joseph Macek. With this formulation a direct measurement of the phase and the magnitude of the excitation scattering amplitudes becomes possible. As polarized electrons and laser selection and analysis techniques become more accessible, the one-electron atom experiment where theory and experiment are more directly comparable will come under closer scrutiny.

Let us turn from this work, which is usually performed on ground states or low-lying excited states, to the burgeoning study of very highly excited atoms and molecules. Here the laser has been the critical new tool that enables these states, the "Rydberg"

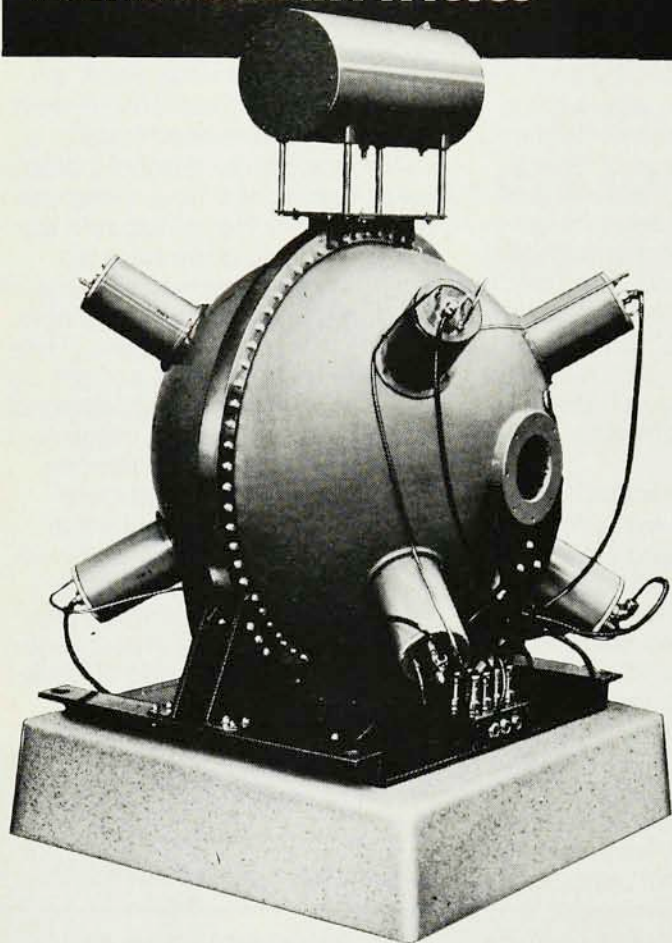
states, to be prepared either directly or, more commonly, in combination with a second laser or a collision process. Rydberg atoms (and, increasingly now, molecules) represent another of nature's laboratories that so often have appeared in atomic physics to enable clean and elegant study of single, simple quantum processes. Rydberg states have been and are being used to study a wide variety of phenomena, including: angular-momentum-changing collisions, core polarizabilities, and more generally, atomic wavefunction structure, and magnetic and electric field interactions (including field ionization). Among the interesting and important practical applications are the effects of background thermal radiation on Rydberg lifetimes, which makes this a good candidate as a "quantum" infrared detector.

Why the resurrection?

In the foregoing I have discussed some of the basic scientific and technical ingredients that led to the resurrection of atomic physics. But as well as these technical aspects there were, I believe, other essential ingredients that acted at the right time to cause the present remarkable growth of the field.

These other essential factors were *societal*. At the onset of the post-Sputnik era, a host of military, aeronomic, astrophysical, fusion, and other practical problems arose, all apparently requiring the type of microscopic data that can be characterized as being the output of atomic and molecular physics. The need was for cross sections, oscillator strengths, energy levels, susceptibilities and polarizabilities, electron affinities of negative ions, and in addition, reaction rates, attachment and diffusion coefficients—the entire gamut of static and dynamic properties of atoms and molecules interacting

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with electromagnetic fields or with each other. As a result the field received, in the early post-Sputnik era, the financial attention it required to thrive. This first occurred through the traditional military scientific support agencies, by ONR, and then by ARO and AFOSR. More recently the NSF and DOE (and its several precursors) has taken over principal support of the field.

Notably missing in my account of the history thus far is a discussion of the gas laser—its original debt to atomic and molecular physics, and its present influence on the field. In the case of the helium-neon laser, I believe that its development by Ali Javan, W. R. Bennett Jr and D. R. Marriot was a classic example of “applied atomic physics”—combining elements of spectroscopy, radiation theory, cross section measurements and, yes, gas discharges. Now, almost twenty years later, the present renaissance in atomic and molecular physics is owed in considerable part to the descendants of this first gas-phase (and continuous-wave) laser, as well as the pulsed, high-powered solid-state lasers, and the tunable dye laser. See Peter Franken’s article on optics (page 160) for another and more comprehensive picture of atomic physics, particularly with regard to its interactions with radiation fields.

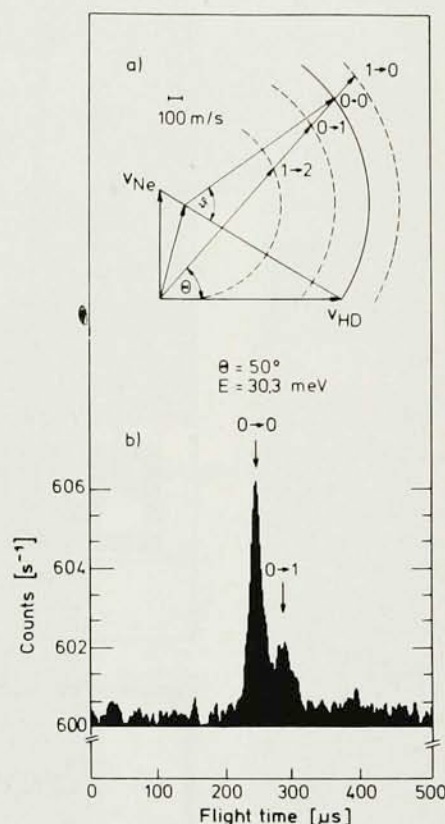
Prospects

Despite the obvious risks attending attempts at prophecy, there are certain aspects of the near-future prospects of atomic and molecular physics that are worth remarking on, particularly with respect to the general question of whether the field will keep its present zesty health. Despite some serious problems (I will note some of these later), it does appear as though there is plenty of the zest left. I believe this opti-

mistic view is closely related to the question of technological advances, as indeed was the present renaissance attributable to these in the first place. Were technology to proceed apace, so that we could expect generally improved, say, laser development and computational power, then I believe that much of the most exciting aspects of atomic and molecular physics would inevitably pass on to sister disciplines—notably chemical physics, which is presently in its own state of creative frenzy. But true technological innovations, should they develop, will keep the atomic and molecular pot boiling very busily. I will mention several such examples here, all cases for which the new technology is already visible, or nearly so; that’s what makes these predictions reasonably safe.

First, consider neutral-particle detection. Much of the history of atomic-beams physics was governed by the (non-accidental) fact that only a handful of neutral atomic and molecular systems are easily detectable by surface ionization. (This technique requires in general that the ground-state ionization energy of the atom be somewhat lower than the work-function of a heated metallic ribbon, usually tungsten, platinum or rhenium.) Only the truly noble alkali metals, some alkali-halide molecules and a handful of others (including indium and gallium) can be so detected. Detection of high-lying metastables—such as Lamb’s 2S hydrogen—can also be accomplished fairly easily.

The elements that are resistant to detection include some of the most interesting ones—including H, O, N, C, S. There is good indication that this state of affairs will change in the next few years, thanks to the laser. Single-particle detection by laser resonance, fluorescence or ionization has already been accomplished (though mainly on alkalis). When more intense and shorter-wavelength la-



Newton diagram and time-of-flight spectrum for elastic and rotationally inelastic collisions of HD with Ne. [From U. Buck, F. Huisken, J. Scheuesner and H. Pauly, *Phys. Rev. Letts.* **38**, 681 (1977).]

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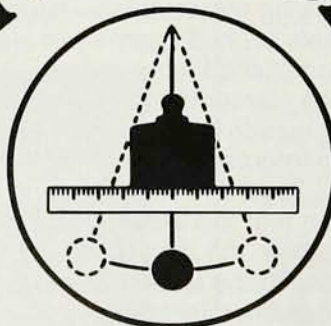
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sers become available, it will doubtless be possible to select or ionize specific atomic systems, even specific states of atomic systems, with efficiencies approaching 100% (or exceeding it, in the sense that an atom can be detected more than once). A workshop devoted exclusively to this subject has just been held at Oak Ridge.

Consider now another aspect of beam detection. In almost all beams experiments in atomic physics, a detector probes one portion of a beam at a time, while the remainder of the beam (which contains almost all the information in the scattering process) is simply ignored. The multichannel array can change all this. It is not a trivial matter to match low-energy atomic beams to such detectors, although at higher energies this has already been successfully accomplished by Johannes Los at FOM and others. Still, there seems to be little doubt that this device will find its way into various forms of beams research, and thereby multiply its information gathering by several orders of magnitude.

The success of the application of lasers has made us hungry for more; nearly everyone in the field is waiting for convenient uv and even x-ray cw lasers to appear on the commercial scene—and it would be difficult to overestimate the effect on atomic and molecular physics when they arrive.

The recent history of collision physics has been intimately linked to a specific area of scientific expertise—namely, that of electron and ion beams technology. Every significant advance in the production of such beams has resulted in new crop of important scientific advances. Will such progress continue? The present absolute limit on energy resolution in the most advanced electron and ion monochromators is a few meV, at best. Are order-of-magnitude improvements to be expected? Difficult metal-surface problems are

significant obstacles to this achievement, and it would not be prudent to anticipate such an advance very soon. Still, it is hard to think of any *fundamental* limitation, so there is a likelihood that monochromators with resolutions better than fractions of a meV will eventually appear on the scene. A host of coherence-type scattering experiments are awaiting appearance of such monochromatic beams. And we must also note the comparable progress made in the production of slow positron beams. It is no pipe dream to anticipate that millivolt-spread, polarized electron and positron beams will appear at some point in the not too distant future.

Growth

Where is the growth likely to be most important in the next five to ten years? Certainly in high-energy atomic physics, a field that is almost embarrassingly rich and will benefit greatly from the availability of improved and higher energy accelerators. The high-energy atomic physicists themselves recently reported their opinions on a five-year outlook of that field. Their views can be paraphrased as follows:

► The three-body problem: by judicious choices of collision partners, the nature of this simplest of many-body problems can be varied over enormous ranges of interaction parameters, making available a most fruitful testing ground for the few-body problem;

► The many-body problem: here, where theory cannot yet match the abundance of experimental information, the stage is set for systematic studies of inner-shell processes, energy transfer, and other many-body collisional effects that can now be explored with a wide variety of diagnostic techniques, including observation of selective excitation and ionization, charge transfer or capture, photoemis-

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sion, positron formation, and alignment and orientation effects. Continuously variable synchrotron radiation sources are becoming increasingly available; such sources are, and will be, used to study important aspects of atomic structure.

► Most importantly, very-high-energy accelerators (GeV) will continue to be exploited in the study of the formation of very high Z , relativistic systems in time-resolved modes.

► Certain serendipitous properties of fast beams are already exploited to perform what are, in essence, low-energy experiments. These include: use of Doppler-shifted radiation from visible lasers to generate effective far-ultraviolet in the center of mass of moving beams; "Coulomb explosions," stripping of ions to states of very high ionization, followed by deceleration, for experiments, including possible ion-trapping, at low energies; "merging-beam" experiments.

► The entire field of the interaction of beams with condensed matter, including energy-loss, channeling, wake phenomena, surface interaction and the like, will open up.

As for the increasing use of state-prepared beams, polarized beams, excited-state beams or combinations of these, and all the other tricks of trade, one knows that these will flourish. After many promising starts that did not really pan out too well (a notable exception being the polarized electron-excitation experiments on mercury by J. Kessler and his col-

laborators at Münster), the GaAs source for polarized electrons has arrived. It works and it will become (is indeed already becoming) ubiquitous.

Ion and neutral-beam traps have a similarly bright prospect. Such traps are of great interest for reasons varying from performance of super-high precision experiments on quantum electrodynamics, through electron-ion collisions and ion-ion reactive collisions—a field that is just now beginning to be tapped.

Interaction of atoms and molecules with ever more intense radiation fields are clearly on the agenda.

In theory, the area of electron correlations in ground and excited states—hitherto very intractable—is beginning to progress rapidly, and signs of "collective" modes are, at last, beginning to appear. General group-theoretic techniques, use of complex hyperspherical coordinates, diagrammatic methods, and other high-brow methods of mathematical physics are being rapidly deployed on atomic problems. In fact, we need another Condon and Shortley to interpret such methods to the new generation of graduate students (and some of their teachers).

Now finally to return to the theme with which I started this article. Suppose a young physicist, having just landed a tenure-track job at a PhD-granting university, or an equivalent job at a research center, were to be faced with a decision on the kind of experimental program to set up. What to

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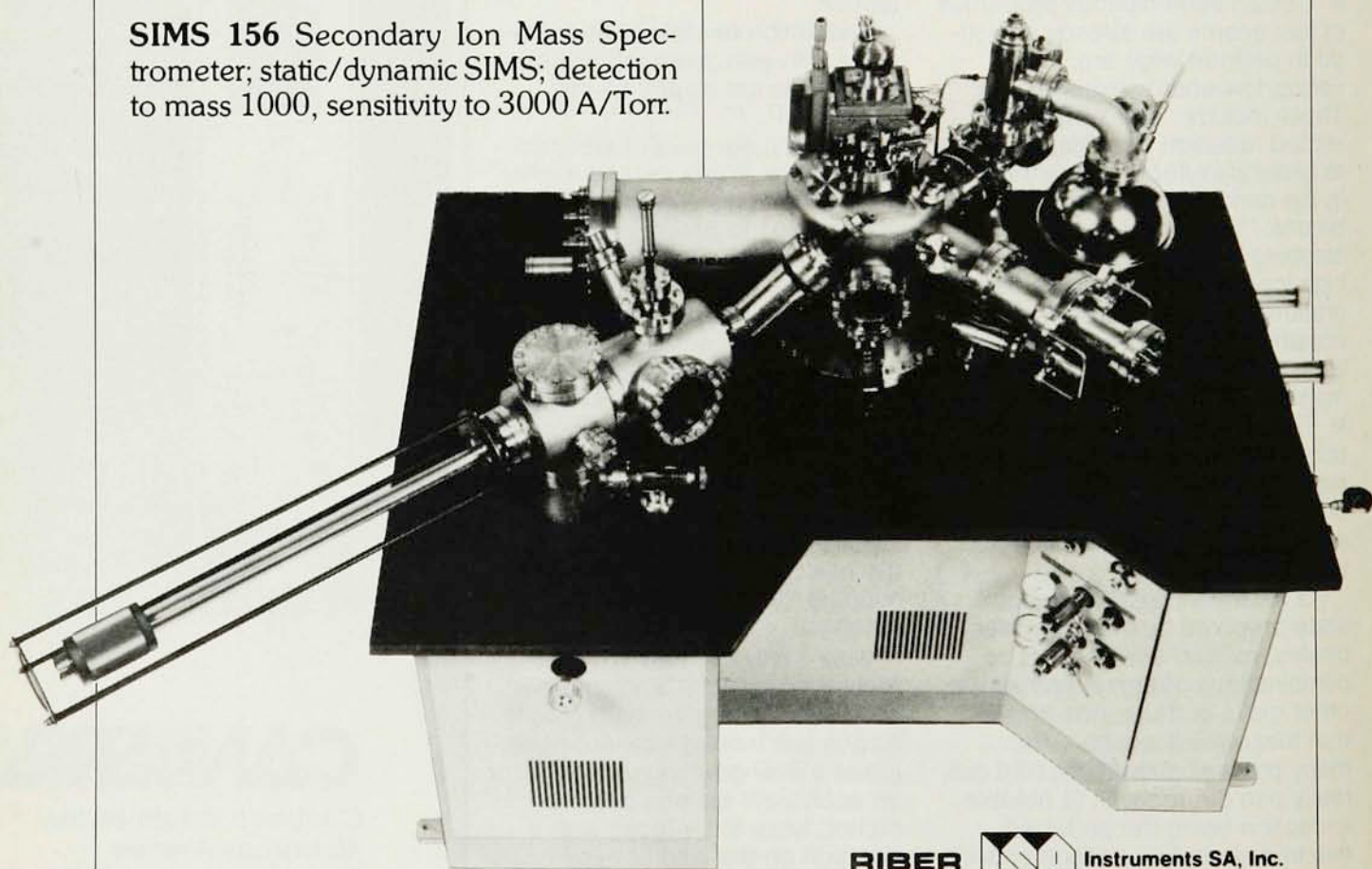
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do? Well, the shopping lists outlined above are long enough for openers, and there are many other areas of equal interest. There should be no lack of interesting and enjoyable problems to attack. But there are problems nevertheless, related as much or more to logistics as to scientific merit. Most of the ideas I have outlined, while perhaps simple conceptually, require very sophisticated and expensive experimental gear. Thus serious problems arise that concern support: first, of course, comes money. Then there is the need for adequate support facilities (machine and electronics shops, computational facilities, general laboratory equipment), availability of good graduate students, the need to acquire, perhaps at the very beginning, some very expensive pieces of equipment, most notably commercial lasers but including minicomputers, ultra-high vacuum gear, and so on. And one needs a comparable variety of skills to manipulate (even, perhaps, to repair) all this high-class hardware. (And maybe a supertalented postdoc!) Not that these problems are not unique to atomic and molecular physics, but we used to be different; shoestring operations, formerly at least marginally viable, are now rather more unlikely to succeed than ever before. And this is not to mention the new, extremely stiff competition now being offered by Western Europe and Japan, where atomic and molecular physics has high visibility, where equipment funds are abundant, and where there are even funds for technicians!

To end on a note of mixed harmony and dissonance, atomic physics will continue to show its characteristic vitality in the near future, but in this author's opinion the days of shoestring budgets and "table-top" experiments are, by and large, past. It will be more

difficult for young people to get solidly established on their own; we will see an increasing concentration of the most advanced research in fewer places. Thus, atomic physics has joined the rest of physics in the mixed blessing of success.

Suggested reading

The most efficient way to obtain a good overview of activities in atomic physics is to refer to the publications of the two major atomic conference series, ICAP and ICPEAC.

Recent collections of the invited talks of ICAP include: *Atomic Physics 7*, D. Kleppner and F. M. Pipkin, eds., 1981; *Atomic Physics 6*, R. Damburg, ed., 1979; *Atomic Physics 5*, M. Prior and H. Shugart, eds., 1977. All are published by Plenum, New York.

Recent ICPEAC collections carry the title *Electronic and Atomic Collisions, Invited Papers and Progress Reports*; they include ICPEAC XI, Kyoto, 1979, N. Oda and K. Takayanagi, eds., North Holland, Amsterdam (1980); ICPEAC X, Paris 1979, G. Watel, ed., North Holland, Amsterdam (1978); ICPEAC IX, Seattle 1975, (U. Washington, Seattle (1976).

See also the annual series *Advances in Atomic and Molecular Physics*, D. R. Bates and B. Bederson, eds., Vol. 16, Academic, New York (1980), as well as a recent series of volumes under the general heading *Physics of Atoms and Molecules*, P. G. Burke and H. Kleinpoppen, series editors, published by Plenum, New York.

In regard to data compilations subsequent to Charlotte Moore's, the Office of Standard Reference Data (D. R. Lide Jr, Chief) continues the NBS tradition of high-quality data compilations, as does the journal *Atomic and Nuclear Data*, K. Way, Ed. (Academic Press). The JILA Information Center (University of Colorado, Boulder, CO 80309) publishes occasional data compilations, critical reviews and bibliographic compendia, as does the Controlled Fusion Atomic Data Center, D. H. Crandall, C. F. Barnett and W. L. Wiese, Eds., ORNL. The report on high-energy atomic physics referred to in the article was prepared at a workshop on accelerator-related atomic and molecular physics in the summer of 1980. Copies can be obtained from the editor, W. E. Meyerhoff, Stanford University, Stanford CA 94305. □

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