Atomic Physicists Meet for Arnold Sommerfeld Centennial

The impact of Arnold Sommerfeld on modern physics has been through his own important and familiar contributions and his role as a great teacher. The importance of his teaching is attested by an illustrious list in the program of the recent memorial meeting at the Ludwig-Maximilians-Universität in Munich, commemorating the centennial of his birth in December 1868, of former students and assistants of Sommerfeld who helped in this celebration.

There was a retrospect into the early history of quantum mechanics by Armin Hermann of Munich and B. L. Van der Waerden of Zurich, a biography of Sommerfeld as a physicist and a prophet of physics by Fritz Bopp of the University of Munich, who organized the memorial meeting, and a very personal story of Sommerfeld as a teacher and as a friend by P. P. Ewald. But much of the meeting and the following symposium on the physics of one- and two-electron atoms, organized by Hans Kleinpoppen of the University of Stirling, was devoted to the present importance of Sommerfeld's work.

Werner Heisenberg, Max Planck-Institut für Physik und Astrophysik, Munich, singled out three subjects in which Sommerfeld maintained a particular interest throughout his life; they were the problem of stability of laminar flow in fluids, the method of complex integration in the solution of physical problems, and the numerical value of the fine-structure constant.

The first of these interests appears to date back to about 1900, when Sommerfeld was engaged, at the Technische Hochschule in Aachen, in engineering problems that led to his hydrodynamic theory of the friction of grease. The flow studies were pursued for a number of years by students of Sommerfeld—Ludwig Hopf and Werner Heisenberg among others. It was some 50 years after Sommerfeld's work before the onset of instability was calculated analytically by C. C. Lin with results in agreement with experiment. Heisenberg then pointed to Sommerfeld's treatment of the propagation of electromagnetic waves over the earth's surface and how this bears on the current problem of scattering of elementary particles by a potential and Regge poles.

Complex integration appeared to be so important to Sommerfeld that, Heisenberg recalled, his older students advised the newer ones: "Do a few integrations in the complex plane in your dissertation and you will get a good grade!" The recognition of the fundamental importance of the fine-structure constant was illustrative of Sommerfeld's physical intuition. He was convinced early that the numerical value was not an accident but that it would be determined eventually by laws of nature. Thus Sommerfeld's ideas have penetrated into the most recent developments of physics.

Solid state. The impact of Sommerfeld's work in solid-state research and technology was described by H. Welker. Sommerfeld had an early interest in the electron theory of metals. The basis of free electrons and Fermi–Dirac statistics proved to be fruitful and many physical phenomena thus became explainable. Studies that followed, on ferromagnetism by Heisenberg, and on anisotropy in magnetic phenomena by R. Becker and his coworkers, resulted in the development of grain-oriented sheet steel that is of great importance today in reducing losses in electrical machinery and in transformers. The era of pure empiricism in the development of industrially important materials, including semiconductors and superconductors, was over.

Hans A. Bethe, Cornell University, reviewed the Bohr–Sommerfeld old quantum theory. He reported that Sommerfeld had difficulty in obtaining good experimental data because of the large Doppler broadening in the hydrogen spectral lines; he therefore relied on the He^+ spectrum. Bethe contrasted this work with the present high-precision measurements of fine and hyperfine structure, the electron gyromagnetic ratio and the Lamb shift, and of muonium. A discrepancy with theory still exists in the Lamb shift. The anomalous g value is being measured at CERN with muons, with an accuracy of $\approx 3 \times 10^{-7}$ in $(g-2)/2$, and ten times better accuracy is still expected. For the two-electron problem the Bohr hypothesis gives the wrong binding energy for helium by over 30 000 cm^{-1}. Bethe contrasted this original result with the variational calculation of Chaim L. Pekeris who used 210 parameters and relativity to obtain agreement in the binding energy to within a few hundredths of one wavenumber.

ARNOLD SOMMERFELD

Alfred Kastler, Ecole Normale Supérieure, Paris, reviewed the optical methods of rf spectroscopy. The emphasis in the last decade has shifted from the problems of creating population differences to coherence effects in the radiation processes. The coherence narrowing, observed primarily in imprisoned resonance radiation, has been studied both in optically excited and in electron-excited systems. Optical pumping techniques have served to obtain relaxation times of the coherence in the atomic magnetization. With suitable systems they can serve as

magnetometers for fields as low as 10^{-7} gauss.

Otto Laporte, University of Michigan, the last of the memorial-meeting speakers, talked on spectroscopy with shock waves. This technique, he said, unifies two favorite subjects of Sommerfeld—spectroscopy and hydrodynamics. The shock tube, with which time-resolved spectroscopy is used, has an advantage over most conventional light sources for the study of the light process itself because the thermodynamic variables are known. Ionization takes place in the gas of the tube. Because heavy gases produce stronger shocks, ionization lowers the achievable temperature as it produces electrons that constitute the lightest gas. The density and absolute-intensity measurements that are obtained are of considerable interest in astrophysical studies.

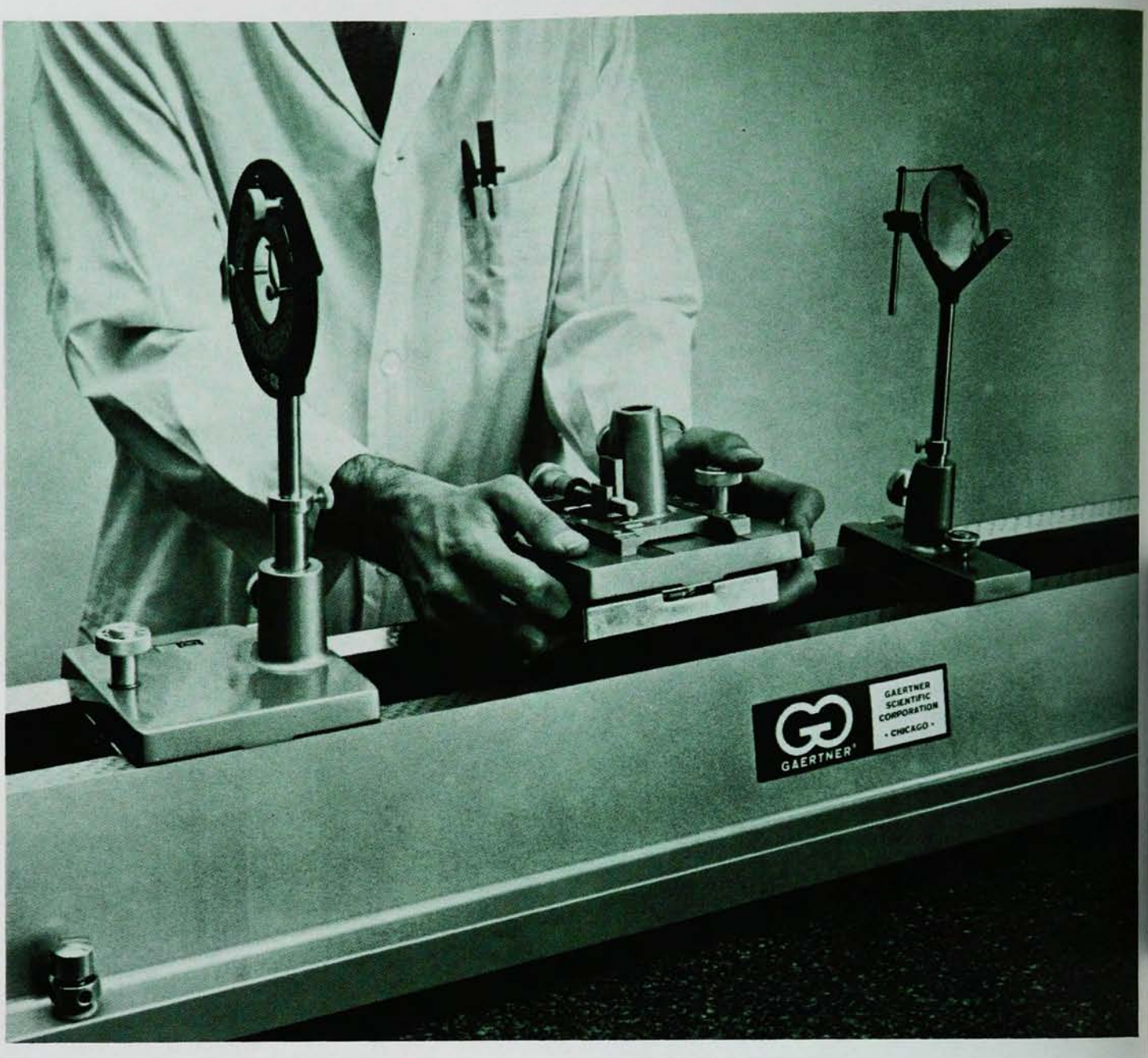
Coherence and interference phenomena have always been important in quantum mechanics but have often been obscured by measurements that do not distinguish between differing quantum states. Now modern experimental techniques have uncovered a wide variety of interference phenomena in both radiation and collision processes.

OERSTED MEDALLIST. On April 23, 1949, in Munich, Lt. Cdr. L. R. Dailey presented the medal to Sommerfeld.

George Series, Oxford University, described how correlations affect the radiation process, with particular reference to the optical double-resonance experiment: A light quantum of appropriate polarization raises the atom into an excited Zeeman sublevel. Radiofrequency excitation then causes a superposition of all Zeeman states with the phases of their wavefunctions locked. When the atom radiates, the different optical frequencies with their phases locked are coherent and produce detectable rf beats. Modulation effects are also observable in absorption, and coherence can also be generated in the excitation process as in a level crossing where one photon is used to excite two degenerate Zeeman sublevels of requisite angular momentum. The observation of coherence is not restricted to steady-state conditions. Modulation effects have been seen in the decaying light following either pulsed excitation with light or electron impact. It was suggested that two different modulation modes could ring at the hyperfine-structure frequency! The conditions for transfer of coherence from the ground state to the excited state in terms of level overlap was also analyzed.

Precision spectroscopy, in which the Doppler effect does not obscure the radiation width, is possible with double-resonance experiments and with the coherence effects in level-crossing experiments.

Hans Bucka, Technical University of Berlin, described such work when the states can be reached from the ground state by photon excitation. If electrons are used in the excitation we remove the restriction imposed by the electric dipole selection rule on the levels that can be reached. The technique in which electron beams, collimated in the direction of the magnetic field, make crossing and resonance experiments possible was discussed by Jean-Claude Pebay-Payroula, University of Grenoble. Application to measurements of fine and hyperfine structure and of lifetimes and g factors in He^3 and He^4 was reported by Jean Pierre Descoubes, Ecole Normale Supérieure, Paris. Claude Cohen-Tannoudji of Paris described an atom in a radiofrequency field as a



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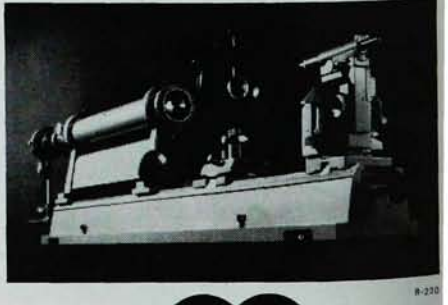

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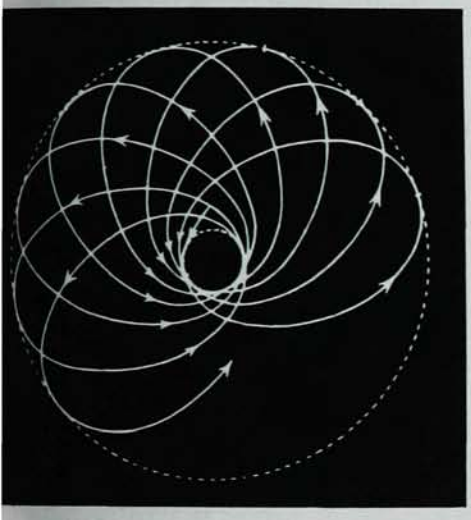
"dressed atom," and showed how this modest description improved our understanding of coherence effects in subsequent optical transitions.

Ian Percival of Stirling University brought back the centennial theme of Bohr–Sommerfeld quantization; the exact predictions of the nonrelativistic energy levels of hydrogen-like atoms by this rule is an example of a "correspondence identity," and it can be explained using the symmetry properties of the hydrogen in terms of interference between alternative classical paths. The exact prediction of Rutherford scattering by classical theory is also a correspondence identity, and has a similar explanation.



In atomic-collision phenomena the role of coherence and interference becomes ever more important as experimental precision increases. Felix T. Smith and Don Lorents of Stanford Research Institute described the theory and experiment of symmetric atom-ion collisions, such as $H + H^+$ and $He + He^+$, in which the gerade and ungerade states allow a choice of two routes to the same final state and the resultant interference phenomena provide a means of measuring the difference between the potentials. Helmut Ehrhardt of Freiburg described experiments on e–He scattering in which the two routes were given by the scattering resonances and the smooth background scattering. In this case variations in angle enabled relative scattering phases to be determined, and also the separate direct and exchange-scattering amplitudes. Hans Kleinpoppen of Columbia and Stirling Universities described how the theoretically predicted coherent effects arising in the polarization of electron-impact radiation, when the hyperfine splitting is not large compared to the line breadth, have now been verified in alkali atoms. The discrepancies between theory and experiment near threshold have mostly been removed.

Precision measurements. E. Richard Cohen, North American Rockwell Corporation Science Center, traced the history of the measurements of the Sommerfeld fine-structure constant to the latest mean value of 137.0366(6), which is based on recent level-crossing and atomic-beam measurements of the energy separation of the $n = 2$ levels in H, muonium hyperfine structure and electron $g - 2$ measurements, and ac Josephson effect in superconductors. A discrepency still exists with the hydrogen hyperfine structure, which, however, involves corrections—such as those for the proton structure. Vernon Hughes, Yale University, reported on the muonium work where, with appropriate pressure-shift corrections, agreement is obtained with this value of the fine-structure constant (see page 36). Glen D. Erickson, University of California, suggested that the Lamb shift and hydrogen hyperfine-structure value could be reconciled in terms of a proton "halo" charge structure without having recourse to deviations from quantum electrodynamics.

However, Norman F. Ramsey, Harvard, told of the almost incredible accuracy of the atomic-hydrogen maser, whose frequency relative to the cesium clock is

$$\Delta \nu_H = 1\,420\,405\,751.786 \pm 0.010 \text{ Hz}$$

which provides an estimate of the fine-structure constant in excellent agreement with that given above. According to Carl Iddings, of the University of Colorado, the theory is still six orders of magnitude less accurate than experiment.

Hyperfine-structure results have been obtained for the He^3 ion. Hans G. Dehmelt, University of Washington, described his observation; ions contained in an electric quadrupole trap become oriented by spin-exchange collisions with oriented alkali atoms. Magnetic resonance in the ions is detectable either by monitoring the degree of orientation of the alkali atoms or the rate of production of singlet or triplet states of helium atoms produced in a charge-exchange reaction.

The possible shift of the magnetic resonance frequency, linear in E, upon application of an electric field has been used by Edgar Lipworth, Brandeis University, Victor W. Cohen, Brookhaven National Laboratory, and Norman Ramsey, to put upper limits on the electric dipole moments of the neutron, electron and cesium atom—respectively 10^{-21}, 2×10^{-24}, 2×10^{-21} e cm. A major difficulty in these experiments is the elimination of effects attributable to motional magnetic fields that the particles experience as they move through the electric field.

The "one-electron" system has become very fruitful in the study of nuclear radii and charge structure. Mme C.S. Wu, Columbia University, reported on recent isotope-shift results in muonic-atom x rays that reflect these nuclear influences. The muon orbit is largely within the nucleus, and it thus serves as a sensitive nuclear probe. F. Boehm, California Institute of Technology, described high-resolution x-ray studies of ordinary atoms that have also made possible the observation of isotope shifts despite the inherently large line widths.

Alexander Dalgarno, Harvard, described the calculation of what appears to be one of the longest lifetimes for a configuration-changing atomic decay—that of the two-photon decay of the helium 2 ^3S state. He obtains an Einstein A coefficient of 4×10^{-9} sec^{-1}. This result is to be compared to a transition probability of 8.23 sec^{-1} for the two-proton decay from the 2s $^2S_{1/2}$–1s $^2S_{1/2}$ state in hydrogen, as recalculated most recently by J. Shapiro and G. Breit.

Norman F. Kroll, Princeton University, gave an illuminating survey of quantum electrodynamics; he pointed out that we are unlikely to learn more about the electromagnetic interactions without at the same time improving on our knowledge of the weak interactions.

More collisions. Sir Harrie Massey of University College London showed how atomic-scattering theory had been influenced by methods borrowed from nuclear physics, but emphasized the additional difficulties that come from the long range of the Coulomb force. There has been satisfactory progress in the application of the truncated eigenfunction (close coupling), variational, polarized-orbital and quantum-defect methods to e–H, e^+–H and e–He, but for more complex neutral atoms agreement for elastic scattering is still not good. The Born approximation is still used in more than half the papers.

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Belfast, described in qualitative physical terms the advantages and drawbacks of the close-coupling and related methods—particularly the difficulty in handling the loss of flux into neglected channels. At low energies the theory is satisfactory but recent experimental advances have raised new challenges, as illustrated in the experimental survey by Stephen Smith of JILA, University of Colorado, Boulder. He described the e–H experiments of J. William McGowan, Gulf General Dynamics, San Diego, near the $n = 2$ and $n = 3$ thresholds. These experiments showed a very elaborate resonance structure that agreed with theory where the theory was adequately precise.

McGowan also obtained experimentally an $E^{1.13}$ threshold law for e–H ionization, which is similar to the early theory of Wannier. The theoretical situation presented by Aaron Temkin, Goddard Space Flight Center, in papers by R. Peterkop of Latvian Academy of Sciences, Riga, and himself was not conclusive. Peterkop showed how the WKB approximation could be used to investigate the relationship between conflicting threshold laws, including those of Wannier and of M. R. H. Rudge and Michael Seaton. Accounts of state-changing atom–atom collisions were given by A. Gallagher of JILA and NBS, Boulder and A. Omont of the CNRS–Science Faculty Spectroscopy Laboratory in Paris. Omont showed that for adiabatic collisions, despite the experimental complications for resonant collisions and theoretical difficulties owing to lack of knowledge of potentials for nonresonant collisions, there is good agreement between theory and experiment for a wide range of processes. These processes include depolarization of resonance radiation, broadening of zero-field level-crossing lines of even and odd isotopes, double resonance, high-field level crossings, hyperfine transfers of population and of orientation. For the impulsive collisions described by Gallagher, such as excitation of excited states, the agreement between theory and experiment is not quite so good.

Atoms, planets and stars. The astrophysical significance of one- and two-electron systems was brought out by Gerhard Elwert, of Tübingen, who described how the polarization of x-ray bremsstrahlung from solar flares could

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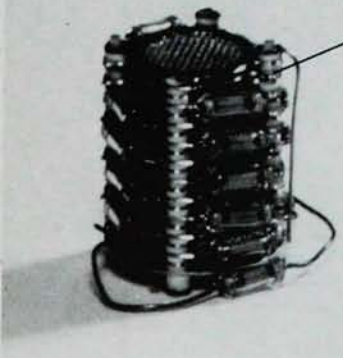

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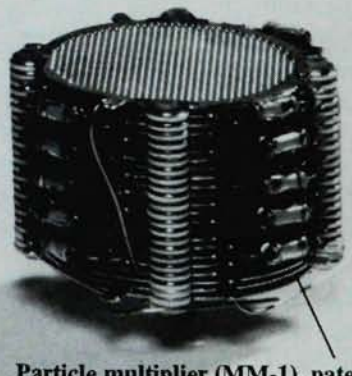

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be used to determine electron-velocity distributions and temperatures of the order of 10^8 K, sufficient to induce nuclear reactions.

The quasistatic and impact approaches in the theories of spectral-line broadening by charged particles were reviewed by Hans Schlüter, University of Bochum. He stressed the importance of taking into account shielding and both electron and ion contributions, and emphasized the effect of similar distortions of the initial and final states, as is required for the highly excited ($90 < n < 253$) interstellar hydrogen lines observed by the radio astronomers. Peter G. Mezger of CSIRO, Australia, reported observations of similar helium lines; he showed how the resultant derivation of the H/He ratio may have cosmological significance.

Fourier spectroscopy was discussed by Pierre Connes, Laboratorie Aimé Cotton, Bellevue. He has brought the Michelson interferometer back to use as a practical spectroscopic instrument by using modern computer techniques to unravel the spectrum. The advantages have been exploited mostly in planetary spectroscopy. Beautiful results were presented of methane spectra from Jupiter and of the carbon-dioxide molecule from Venus.

Recent results, presented in a series of contributed papers, included important theoretical and experimental advances in electron–atom and heavy-particle–atom collisions, beam-foil spectroscopy (particularly fruitful in atomic-lifetime measurements), refinements in other spectroscopic techniques and measurements of atomic constants, and atomic theory. Kastler concluded the meeting by noting how atomic physics is flourishing today in fields from biology to astrophysics, and its influence, in particular quantum electronics, on daily life.

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