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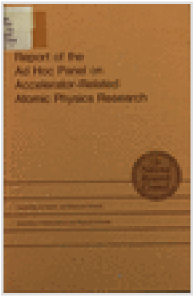

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REPORT OF THE AD HOC PANEL ON ACCELERATOR-RELATED ATOMIC PHYSICS RESEARCH

Committee on Atomic and Molecular Science
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D. C. 1976

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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Gentlemen:

This report deals with the emergence of an increasingly important new subfield of physics, in which accelerators are used for the study of atomic inner-shell transitions, collisions, and the properties of highly ionized and excited atoms. While the excitation and subsequent behavior of atomic inner shells have long been studied in connection with x rays and Auger electron their systematic study in connection with the collisions of heavy ions is a relatively new field of endeavor. The report outlines the present research activity in this new area, its recent accomplishments, many of its open problems, and its prospects and challenges. It also outlines some of its current connections with practical areas of application, ranging from the detection of trace species by x-ray fluorescence analysis to the measurement of the collisional and radiative properties of highly excited impurity ions that are expected to have a crucial influence on the behavior of plasmas in fusion reactors.

The new field of research in atomic inner-shell and high-energy collision processes and spectroscopy depends on the use of accelerators operating in energy ranges that were recently considered the exclusive domain of nuclear physics. Without the existence of current accelerator resources, which were constructed almost exclusively for nuclear research purposes, knowledge in this new area of inner-shell physics would be almost nonexistent. Its development and present state of high activity testify to the fruitful consequences of interactions in both resources and personnel between the areas of physics classified, respectively, as nuclear and atomic science.

Because of its dependence on facilities of substantial size and cost, accelerator-related atomic physics requires special attention on the part of funding agencies responsible for both pure and applied research in its field; because it has thus far been able to grow through the use of accelerators that were initially constructed under nuclear auspices, full recognition of the needs of this promising research field has not had to be faced in the budgeting process. It is clearly unwise for the resources available to this field to remain dependent on decisions that are determined primarily by the changing priorities of nuclear science. The Panel that has prepared this report recommends that the special needs of this field be explicitly recognized and responsibility assumed by appropriate agencies of the federal government.

The peculiar position of this subfield, closely associated with nuclear physics in its needs for major facilities, but having its basis of concepts and common language in atomic and molecular science, calls for special and continuing effort in maintaining liaison and information flow among the communities that are involved. The Panel's report points to these needs and recommends actions to meet them. In carrying out its task the Panel has also provided a significant and interesting summary of a promising field of scientific endeavor.

Yours sincerely,

/signed/

Felix T. Smith, *Chairman*
Committee on Atomic and
Molecular Science

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CONTENTS

SUMMARY

BACKGROUND

Research in fundamental atomic physics with the use of accelerators and other large machines is a rather new field of endeavor. It has not yet been generally recognized as being in a separate domain, yet its characteristics and requirements set it off quite distinctly from such fields as traditional atomic spectroscopy, nuclear physics, and plasma physics, albeit funds for it are often provided under one of these categories.

At its April 23, 1974, meeting, the Committee on Atomic and Molecular Science, of the National Research Council's (NRC) Assembly of Mathematical and Physical Sciences, agreed that it would actively explore two aspects of the connection between accelerators and atomic physics research: (a) questions associated with large and unique national installations and (b) means of facilitating effective interaction of atomic physicists in the use of local accelerator laboratories at universities and other institutions. Accordingly, the Chairman of the Committee established an *ad hoc* working panel to conduct a study of these concerns. In December 1974, the panel was expanded and charged additionally with the preparation of a report that would summarize the current status of research in accelerator-related, inner-shell atomic physics; identify major needs; and formulate recommendations for action by the scientific community and government agencies. This report is the outcome of this task.

FINDINGS AND RECOMMENDATIONS

Current research in accelerator-related atomic physics deals with

1. High-velocity binary ion-atom collision processes in hitherto unexplored regimes, which lead to the capability of calculating cross sections, transition rates, and excited-state populations needed to treat the behavior of more-complex systems;
2. Photon and electron spectroscopy of the decay of projectile atoms excited in high-energy beams, from which information about atomic structure and fundamental electrodynamic interactions is obtained;
3. The application of techniques from other branches of atomic physics, such as laser excitation, to the study of specific states of ions in beams;
4. Exploration of the interfaces between atomic and nuclear physics and between atomic and solid-state physics, as well as of technological applications ranging from x-ray fluorescence analysis to laser design.

The rise of the physics of highly excited atoms, studied with accelerators, marks a new phase in the study of fundamental interactions that involve electrons, heavy ions, and photons. Both experimental and theoretical aspects of the field are being actively investigated, as reflected by the number of publications and papers presented at scientific meetings and by the number of persons engaged in this research. Approximately 400 investigators are conducting work in atomic physics in over 40 accelerator laboratories in the United States. In some other countries the field is being pursued with even greater vigor.

On the basis of its study, the panel has formulated recommendations reflecting its main conclusion that atomic physics with accelerators must be identified as a rapidly evolving, coherent, and distinct new field of scientific research with important and immediate technological applications. The peculiar needs and potentialities of this endeavor should be recognized by the scientific community and funding agencies. In the face of developments elsewhere, competence, if not leadership, in this field in this country can be maintained only through a concerted and more nearly adequately supported effort. The panel's recommendations follow:

1. Because atomic collision processes initiated by the impact of keV- and MeV-energy ions now constitute a clearly identifiable, large subfield of atomic physics, with peculiar needs and capabilities, *we recommend that, for purposes of budgetary classification and scientific planning, research with accelerators in inner-shell atomic physics be recognized as a separate, coherent subject.*

2. An effort should be made to facilitate the use of accelerator laboratories for the study of atomic phenomena by investigators from other institutions. Because impact velocity rather than energy is a critical parameter in most atomic collision processes, it is often necessary that an experiment initiated on one accelerator with one particular atomic system be completed on another accelerator that is suitable for the study of another related system. *We recommend that adequate funds be provided for competent investigators to use suitable accelerator facilities, and that laboratories operating such facilities make a strong effort to accommodate outside users engaged in atomic research.*

3. Recognizing that certain unique accelerator facilities, with capabilities beyond those of conventional two-stage tandems, are appropriately shared through cooperative arrangements by research workers in many fields, *we recommend that inner-shell atomic physics, with its complex experimental apparatus, be regarded as a legitimate component of the activities of such laboratories and that the anticipated needs of this research field be considered early in the design of new installations, such as the Holifield Heavy-Ion Research Facility at Oak Ridge National Laboratory.*

4. In view of the momentum and the significance of research in accelerator-related atomic physics, the frequent need to maintain complex apparatus on line for protracted periods, and the desirability of maintaining a multifaceted and regionally distributed research effort in this expanding field, *we recommend that serious consideration be given to proposals for the conversion of some selected existing accelerator laboratories and the construction of certain additional installations to be dedicated primarily to atomic physics.*

5. We note that the new forms of spectroscopy (beam-foil, collision, quasimolecular x-ray), which have arisen

from atomic physics conducted with accelerators, are being supported widely in some European countries, notably in Germany. *We recommend that U.S. funding agencies remain aware of the importance of maintaining competence, if not leadership, in this field of research in the United States.* Of particular concern is the lagging support for gifted young physicists.

6. *We recommend that support of graduate students and postdoctoral research associates in inner-shell atomic physics be maintained, because of the broad training that this field provides and because of its wide interconnections with other research specialties, thus affording students considerable flexibility and preparing them for a range of possible jobs.*

7. *We recommend that the Committee on Atomic and Molecular Science assume continuing responsibility for coordination in accelerator-related atomic physics, establishing liaison where appropriate with the Committee on Nuclear Science and with scientific organizations such as the Division of Electron and Atomic Physics and the Division of Nuclear Physics of the American Physical Society and (through the use of* ad hoc *panels or other means) (a) maintaining communication among physicists engaged in research with accelerators on highly excited atoms; (b) maintaining liaison with funding agencies and the nuclear community in order to advise inner-shell atomic physicists promptly on possibilities of access to heavy-ion accelerators and on the availability of such machines for transfer; (c) maintaining and updating information on activity in accelerator-related atomic physics, including level of effort, personnel, and placement of graduates; and (d) acting as a central clearinghouse for the exchange of information on problems encountered by researchers in this field.*

ORGANIZATION OF THE REPORT

Following a brief introductory section, an outline of the current status of inner-shell atomic physics is presented in Chapter 2. This outline is not intended to be complete or exhaustive but merely indicative of work now being conducted in the United States on this subject. Considerable detail is given in some cases by way of example; other topics are only summarized; and still others are omitted.

The level of effort in accelerator-related atomic physics research in the United States is gauged in Chapter 3 on the basis of a survey conducted by the panel.

Unsolved problems and major challenges in this field of research are indicated in Chapter 4, which also contains a discussion of the overlap of inner-shell atomic physics with other scientific disciplines and with technology.

Research conducted with electron accelerators is not included in this report. Work with synchrotron radiation sources and with machines primarily designed for controlled thermonuclear reaction (CTR) research and related unique facilities is briefly discussed in Appendixes A and B.

1 INTRODUCTION

It is difficult to imagine how physics might have developed during the past 50 years without accelerators for charged particles. The entire field of strong interactions, from the structure of light nuclei to the production of strange new particles, has been dependent on the introduction of a variety of machines that produce collimated beams of particles with well-defined energies.

Not surprisingly, beginning with the discovery of the neutron in the early 1930's, most physics experimentation with accelerators became directed toward a better understanding of nuclear forces and nuclear structure. Throughout this period, atomic physicists only on rare occasions took advantage of the availability of accelerator beams of energetic charged particles to study atomic collision processes at high energies. Besides the natural fascination exerted by the mysteries of nuclear structure, the difficulties associated with the detection of atomic collision products under conditions prevailing in an accelerator laboratory probably accounted, until recently, for the almost total neglect of this experimental field.

Following the early development of quantum mechanics, the theory of energetic collisions between ions, electrons, and atoms enjoyed considerable progress during the 1930's and 1940's, as expounded in successive editions of the well-known treatise of Mott and Massey* and other books and reviews. Many of the calculational techniques put forward during this period--Born approximations, impact-parameter perturbation theory, distorted-wave theory, the Brinkman-Kramers treatment of electron transfer--are particularly suitable for describing fast collisions in which the time

*N. F. Mott and H. S. W. Massey. *The Theory of Atomic Collisions* (Oxford University Press, London, 1976).

of interaction is extremely short. Yet, few experimental measurements were undertaken to confirm the validity of the theoretical predictions and to establish their limits. Exceptions were determinations of stopping power in targets, where the energy loss could be measured with instruments, such as electrostatic and magnetic analyzers, available in nuclear physics laboratories. These effects and others such as the distribution of charge states of a projectile moving through matter, although fundamentally atomic in nature, are manifestations of average and bulk properties and thus accessible to comparatively coarse detection techniques. The study of most atomic single-collision processes, however, required the introduction of more sensitive, delicate, and elaborate methods.

Because virtually all MeV-level accelerators were designed for use by nuclear physicists, it is easy to trace the atomic physics activity at these "high" energies in terms of its compatibility with the ongoing nuclear experimentation. Thus, most accelerator-related atomic physics has been conducted as a "piggyback" operation in nuclear laboratories and has had to be restricted to the use of techniques that are typically available in such settings. For example, measurements of the total yield of characteristic x rays from the bombardment of solid targets by protons and alpha particles, using proportional counters, NaI crystals, and, more recently, Si(Li) detectors, are experiments that are readily adaptable to a nuclear physics environment, and much excellent work of this type has been undertaken. As the total cross sections for the production of inner-shell vacancies in atoms are large--especially when contrasted with cross sections for nuclear processes--the demands on beam time are modest, and effective work is possible in "symbiosis" with nuclear physics.

More recently, it has become apparent that careful and thorough measurements of detailed features of specific atomic collisions would advance the field; a fuller understanding of the mechanisms of the collision processes is within reach but depends on much more refined measurements than those of total cross sections, average energy losses, and the like. This does not mean that the fruitful collaborations between nuclear and atomic physicists should be terminated or even discouraged. Rather, it suggests that accelerator-related, inner-shell atomic physics should be recognized and identified as a productive field of research in its own right.

Good experimental research in this field has certain characteristics that arise from the nature of the physical processes that are under investigation. Typically, the demands on experimental arrangements are as follows: variable ion energy, so that the same velocity range can be attained for heavy ions of different mass; versatile ion sources, so that systematic studies of isoelectronic sequences can be conducted; facilities to prepare initial ion states by prestripping in foils, gas cells, or electromagnetic fields; high beam intensity, to permit high-resolution spectroscopy (low-intensity beams, however, are adequate for total-cross-section and particle-counting experiments); very high vacuum, extending to ultrahigh for proposed experiments on ion excitation; availability of particle detectors, photon detectors, spectrometers, fast electronics, logic circuitry, and computational facilities. In some cases, the size of gas-cell pumping stations and of apparatus for collimation to study small-angle collisions makes it necessary to provide large experimental areas; this requirement must enter into early planning considerations.

In the following chapter, the current status of research in accelerator-related atomic physics is briefly reviewed and the more easily discernible future directions of such research are outlined. The subject is divided into four parts: the processes involved in high-velocity binary collisions between ions and atoms; the photon and electron spectroscopy of the decay of projectile atoms excited in high-energy beams, from which information about atomic structure and fundamental electrodynamic interactions is obtained; the exploration of the borderlines between atomic and nuclear physics and between atomic and solid-state physics; and a sample of interesting technological applications of accelerator-based atomic physics. The examples cited are intended to illustrate the breadth and depth of studies that have become possible with the introduction of modern facilities and techniques in inner-shell, accelerator-related atomic physics. The list is by no means exhaustive, but it is indicative of a fast-moving and exciting new scientific frontier.

2 SURVEY OF ACCELERATOR-RELATED ATOMIC PHYSICS RESEARCH: PRESENT STATUS

I. HIGH-VELOCITY ION-ATOM COLLISION PROCESSES

The study of ion-atom collisions is one of the richest areas for exploring the interactions between electrons and nuclei. Because the velocity of a loosely bound electron corresponds to an energy of ~25 keV/amu, ion accelerators in the range of ~100 keV, with which this report is concerned, permit a great variety of investigations involving excitation of the collision partners. Although the fundamental electromagnetic interactions governing the behavior of most systems are quite precisely known, the conditions under which ion-atom collisions take place can be varied widely and easily. Thus, the collision velocity can be controlled and the collision partners can be chosen from throughout the periodic table in various states of electronic excitation and ionization.

The quantum theory of the atom took its initial impetus from the empirical fact that in ordinary encounters with other atoms or molecules, such as in gas kinetic collisions, atoms prove to be remarkably stable and immune against external influences. Atomic collision physics seeks an understanding, on the basis of quantum mechanics, of the great diversity of physical phenomena that can be observed as a result of the disruptive intervention caused by a violent encounter between two atoms.

Remarkably complex physical phenomena are observed in the conventional spectroscopy of diatomic molecules, which is the study of bound or nearly bound states of systems containing two nuclei and a number of electrons; hence, it is hardly surprising that "ion-atom collision spectroscopy," which deals with unbound states of diatomic systems, should present an abundance of physical effects that challenge understanding.

Starting with the simplest situation, we consider the gentle perturbation of a target atom by the swift passage of a heavy charged particle, assuming the projectile to have low charge (such as in the case of an incident proton) and sufficiently high energy so that the interaction time is short. In this limit, a perturbation description is applicable, and we expect that the target will be excited and ionized, but with low probability. This is indeed the case, and the processes that occur are generally well understood for both ionization and discrete excitation of outer-shell as well as inner-shell target electrons. Total cross sections and mean energy losses in such collisions are well accounted for by the Bethe-Born theory of inelastic collisions. However, even here interesting information can be obtained, since the determination of certain important atomic properties such as oscillator strengths can be achieved, supplementing similar information from the interaction of photons or electrons with atoms.

The traditional paradigm of a collision of this kind is that between a proton and a neutral hydrogen atom. Countless theoretical methods have been devised to describe the excitation and ionization of a hydrogen atom by collision with a proton, and new calculational approaches are still being proposed and tested.

Collisions of protons with inner-shell electrons in heavier atoms are analogous to proton-hydrogen collisions but with the added experimental advantage that the subsequent decay of the excited atom can be easily monitored through observation of x rays or Auger processes. Furthermore, heavy atoms in which levels with principal quantum numbers n = 2-4 may be inner shells--and are thus effectively shielded from the perturbations of the outer shells--provide an opportunity to study collisions with electrons that are initially in a state other than the 1*s* ground state of a hydrogenic atom.

Even the relatively simple Coulomb-perturbation regime for ion-atom collisions raises a number of questions to which only partial answers are now available: How does the probability for the occurrence of various inelastic processes depend on the impact parameter for the collision? Or, how do distant and close collisions compare in effectiveness? To what extent is it possible to align atoms in such energetic collisions? Are multiple excitations possible? What are the differential, rather than total, cross sections for emission of electrons as functions of electron energy and angle of emission? How important are relativistic corrections in treating the atomic electrons?

As the strength of the interaction is increased, either by the use of higher-Z projectiles or lower collision velocities, many of the questions, which in a perturbation regime could be analyzed with reasonable confidence, become of central importance but no longer yield to a simple first-order understanding. It becomes imperative to seek guidance from experiment and to study in detail the various phenomena that can occur.

As the projectile atomic number increases and approaches that of the target, the projectile-electron interaction cannot be treated as a weak perturbation. Excitation and ionization probabilities reflect the departure from the weak perturbation regime by slow departures from a simple Z^2 proportionality, which is the hallmark of perturbation theory as well as of Rutherford scattering.

For low-Z projectiles, however, it is still possible to describe the physical situation by making corrections to the first-order perturbation results. The impinging particle distorts the state of the target atom, and the distortion is manifested by a lowered effectiveness of the collision at low velocities, because of a tighter binding of the atomic electrons, and an enhancement of the yield at high velocities, where dynamic distortions make themselves felt.

If the projectile Z approaches the target Z in magnitude, as in collisions between two heavy atoms, the electronic binding forces of both atoms become dominant in describing the time evolution of the system. At the extreme of low collision velocity, it is possible to account for many qualitative features in such collisions by assuming that the electrons have sufficient time to establish well-developed orbits around the two nuclei, which may be considered almost stationary at any given instant. Transitions from and into these orbits can be studied and a description in terms of quasimolecular orbits established. In this manner, an entirely new field of spectroscopy has been opened by the detailed study of low-energy ion-atom collisions. These processes, qualitatively understood in the different collision regimes of energy and atomic number, are subject to quantitative test in current research efforts.

Inner-shell ionization cross sections have been measured extensively at a number of accelerator laboratories for proton, deuteron, and alpha-particle impact on a variety of targets, over a wide energy range. The general trends of the results are consistent with predictions of direct-Coulomb-ionization theories based on a classical binary-encounter approximation or a plane-wave Born approximation.

Most of the experimental work has been carried out at velocities below that at which the ionization cross section peaks; current research in this regime centers on the quantitative interpretation of small but systematic discrepancies between theory and experiment. These deviations from the first-order theories have been explained in terms of Coulomb deflection of the projectiles and of increased binding of the target electrons during the collision. At velocities above the peak of the ionization cross section, less systematic experimental work has been performed, but it has been concluded in general that the asymptotic form of the plane-wave Born approximation agrees with experiment at high energy, but that the binary-encounter calculations fall off too rapidly.

For heavier projectiles, there is growing empirical evidence for several inner-shell ionization phenomena that are only partially understood. The rich x-ray and Auger-electron satellite spectra observed in high-resolution studies of heavy-ion/atom collisions indicate that a high degree of multiple ionization occurs in these collisions. On analysis, results generally appear to be consistent with a binomial distribution of additional vacancies produced in the target inner shells; the theoretical basis for the large probability of ionizing several inner-shell electrons independently is, however, not clear. Departures from a binomial distribution of satellite-line intensities have now been observed. A large number of multiplet states of highly ionized atoms are formed by heavy-ion impact. Interpretation of the data is made complicated because the fluorescence yield used to convert x-ray yields to ionization cross sections in heavy-ion collisions can differ greatly from the fluorescence yield of singly ionized atoms. (See Section II.A.)

Ionization cross sections measured with heavy-ion projectiles have been compared with first-order Coulomb ionization calculations, which scale as the square of the projectile nuclear charge, for constant projectile velocity. Although agreement between theory and experiment is fair in many cases, the reasons for such agreement must be considered phenomenological as the first-order theory has been extended beyond its limits of validity. The ionization probability during a close heavy-ion/atom encounter is so large that perturbation-theory techniques are hardly applicable.

A recently discovered phenomenon in heavy-ion collisions is the strong dependence of x-ray production cross sections on the electronic charge of the projectile ions. In some cases it is now clear that multiple outer-shell ionization in the target atom changes dramatically with projectile configuration, so that the striking changes in x-ray yields are brought about primarily by fluorescence-yield changes. In all cases, however, there is a real change in inner-shell vacancy production with different projectile charge states; the cross sections increase significantly as the last few electrons are removed from the incident ion. Although this phenomenon has been interpreted in terms of electron screening, and of charge transfer to bound states during the collision, neither a quantitative theoretical model nor a systematic experimental study of the influence of all collision parameters has yet been made.

In low-velocity heavy-ion collisions in nearly symmetric systems, a strong enhancement of inner-shell ionization cross sections just above threshold has been observed. Electron promotion between shells due to rotational and radial coupling between molecular orbitals that change throughout the encounter has been invoked successfully to explain this enhancement. A quantitative theoretical model has been developed that describes electron promotion in adiabatic collision systems, but it is more difficult to account for the observed strong enhancement in inner-shell ionization at higher velocities, beyond the adiabatic domain, when target and projectile levels are comparable. Cross sections oscillate as a function of target or projectile atomic number. The nature of the reaction mechanisms and the details of vacancy-sharing in such collisions are the subjects of much current research. Interpretations have been based on the influence of molecular-orbital coupling, even during the short interaction times in these high-velocity collisions; it is clear, however, that the importance of multistep or multielectron processes needs to be fully considered before a complete understanding of the reaction mechanisms can be reached.

Strong evidence for the formation of quasimolecules in ion-atom collisions is derived from the observation of continuous radiation extending to higher energies than those of the characteristic x-ray lines of the collision partners. This radiation has been associated with the decay of states of transient molecules containing inner-shell vacancies in molecular orbitals that are depressed from atomic energy levels during the time of the collision. A theoretical description in terms of both induced and spontaneous decay of transient inner-shell states has constituted the basis for considerable research on the photon spectrum, anisotropy, and production cross sections of continuous quasimolecular radiation (see also Sections II.A and II.C). Research on this subject at numerous accelerator laboratories has been particularly stimulated by predictions of spontaneous positron emission, expected to occur if vacancies can be produced in molecular levels with binding energies that exceed $2\,mc^2 = 1.02$ MeV. Positron emission may thus take place if the sum of projectile and target nuclear charges exceeds a critical value $Z_{cr} \sim 150$. Preparations for experiments on this phenomenon, entailing significant tests of quantum electrodynamics, are under way at the new UNILAC accelerator at the Gesellschaft für Schwerionenforschung in Darmstadt, West Germany, and at the Berkeley HILAC. Predictions of the expected positron yields hinge on the probability that a vacancy exists in the inner-shell orbitals of the collision system. There is no agreement, at present, on the magnitude of this probability, and only further experiment can shed light on this problem.

Vacancy formation in atomic collisions depends strongly on the impact parameter or scattering angle in a collision. Significantly different impact-parameter dependence is predicted for direct Coulomb ionization and for electron promotion by rotational coupling or by radial coupling. Using coincidence techniques, several experimental groups have determined the probability distribution of vacancy formation as a function of impact parameter. In collisions of light projectiles with heavy targets, the ionization probability is found to increase as the impact parameter is reduced; these experimental results agree well with Coulomb-ionization theory. In symmetric collision systems at low velocity, inelastic energy-loss studies have shown that there is a large probability for inner-shell ionization if the impact parameter is comparable to the inner-shell radius. Direct measurements of the impact-parameter dependence of the ionization probability have also been made in several of these collision systems; the results agree with calculations based on rotational coupling between molecular orbitals. At higher velocities, an enhancement in the ionization probability has been found for symmetric collisions; this observation reinforces suggestions that rotational coupling remains important at velocities that lie considerably above the adiabatic regime.

Atoms that have been ionized in inner shells through heavy-ion collisions can be in any of a very large number of states. Little is known about the manner in which specific states are populated in collisions. Among others, metastable states are formed in relative abundance; it has thus been possible to measure the lifetimes of long-lived few-electron configurations along isoelectronic sequences. Some collisional quenching parameters have been measured for metastable states of He ions, but for heavy-ion states no quenching rates have yet been determined. The dramatic influence of quenching processes on inner-shell vacancy states has recently been demonstrated, however, through the measurement of x-ray yields that are not proportional to target thickness because the vacancies are filled through competing processes in a solid.

Significant alignment and orientation of outer-shell states excited in ion-atom collisions have been found through standard optical techniques. Anisotropic angular distributions were observed in the intensity of x rays produced in some heavy-ion collisions; these give evidence for the alignment of the inner-shell states formed in the collisions. There is as yet no quantitative theoretical understanding of the mechanism through which such aligned atomic states are produced, although qualitatively it is clear that electron capture to excited states plays an important role in selectively forming certain substates.

The importance of electron-capture processes in a number of heavy-ion collision phenomena has recently become apparent. In some cases, the capture of target-atom inner-shell electrons by the projectile is expected to compete with other inner-shell ionization mechanisms. Although this hypothesis still awaits definitive experimental test, it has been used to explain the trends of many observed results. It has been established that loosely bound target electrons are captured predominantly to excited states of heavy-ion projectiles; the large capture cross sections appear to account for the intense inner-shell radiation from highly stripped heavy-ion projectiles.

Considerable effort has been devoted to experimental and theoretical studies of electron-capture and -loss processes. Even though calculations agree with observed data for proton-hydrogen collisions, no quantitative theory exists that can be applied successfully to electron capture by heavy ions. Equilibrium charge fractions can be estimated accurately through simple models that assume that outer-shell electrons are stripped off at relative velocities that are comparable with the orbital electron velocity. There is no success to date, however, with calculations of electron-capture cross sections for any ions heavier than hydrogen. Experimental capture and loss cross sections are available for a variety of collision systems over scattered energies. Interpolation and even extrapolation are the best available techniques to estimate cross sections in regions for which experimental results are not available.

Cross sections for electron capture by protons from atoms have been measured for a number of final states. The results are interpreted successfully in terms of first-order Born-approximation theory developed many years ago. Nevertheless, the validity of the theoretical formulation has recently been challenged. This criticism is supported by the results of new measurements in which coincidence techniques were employed to look only at the capture of tightly bound electrons. At present, work is in progress on reformulation of the theory and on measurements of the impact-parameter dependence of the capture of tightly bound electrons.

Heavy ions capture loosely bound electrons mostly to excited states; tightly bound electrons are expected to be captured to the ground state. The former process gives rise to prolific radiative decay of the projectiles; the latter ionizes the target atoms in inner shells. Preliminary cross sections have been reported for these processes, but no systematic study of the cross-section trends with various collision parameters has yet been made.

II. DECAY OF STATES EXCITED IN FAST PROJECTILE ATOMS

A. Transitions in Excited Atoms

Atomic transition probabilities in the optical (outer-electron) regime have been studied for a long time, but only recently has there been a growing effort to investigate the de-excitation of atoms that contain deep-lying vacancies, are highly ionized, or have several electrons in excited bound states. The almost explosive evolution of this subject has come about through the development of techniques for creating highly excited atoms with ion accelerators and the elaboration of theoretical approaches, including the use of large-scale computers. The knowledge gained has added information of previously unsuspected importance--both from the point of view of fundamental science and with regard to technological applications.

The de-excitation of atoms that initially have vacancies in inner shells generally occurs by the competing processes of photon emission and radiationless transitions. The width of an excited state (or the reciprocal of its lifetime) is determined by the sum of decay probabilities through these channels. One important property of an excited state is the relative probability of radiative de-excitation or the fluorescence yield; this is the ratio of radiative width to the total width of the state.

Auger-electron emission has been observed and calculated since the 1920's. Rather thorough and painstaking measurements of Auger spectra have been undertaken in the last decade; the level of effort has increased rapidly with the growing interest in inner-shell processes and in solid-state and surface effects revealed through radiationless transitions. Systematic and extensive calculations of Auger and Coster-Kronig transition probabilities have only been initiated in the last few years and are as yet incomplete.

The greatest shortcoming of experimental and theoretical work on Auger processes, until most recently, has been its limitation to single-vacancy initial states. This is a severe restriction. When an inner-shell vacancy is created in an atom, the state decays through a *cascade* of Auger and radiative processes. Generally, the Auger transition rate is several orders of magnitude greater than the radiative rate; only K-shell vacancies in medium and high-Z elements and L-shell vacancies at high Z constitute exceptions to this rule. In the first step of a radiationless process, the decay of a single vacancy leads to two vacancies in less tightly bound shells (or subshells, in the case of Coster-Kronig transitions). Only this first step has so far been studied in detail. Characteristics of the subsequent cascades of de-excitation events have merely been touched on in most general, statistical terms; final charge-state distributions have been observed in a few cases. The characterization of the states of multivacancy atoms and the formulation of theoretical Auger transition rates between terms of multivacancy ions are only now being developed.

The complex and almost untouched subject of the details of Auger cascades calls for an aggressive exploratory effort, on grounds of both basic theory and relevance to plasma physics and astrophysics. Because it appears likely that in the course of Auger cascades significant population inversions can arise, these studies may contribute to the design of high-energy lasers.

The subject is complicated. In atoms that contain several vacancies, the holes couple to form multiplet states. Radiative and Auger rates can differ widely among these states. It is for this reason that the x-ray signature, the final charge state, and other characteristics of the multistage decay of highly excited atoms are difficult to calculate. In particular, Auger or x-ray decay channels, or both, may be closed for some multiplet states. Atoms in such states can be metastable, or radiate with very high probability, causing the decay characteristics to deviate widely from the average over states.

The creation of multiple atomic inner-shell vacancies under controlled laboratory conditions has become possible through the use of heavy-ion accelerators for ion-atom collisions, as discussed in Section I. Calculated transition rates between multiplet states have been compared successfully with measurements in recent months. Argon L x-ray spectra from $Ar^{+} \rightarrow Ar$ collisions in the 50-200 keV range and Ne K x-ray spectra produced in the bombardment of Ne with 30-MeV O^{5+} ions, for example, were analyzed according to charge states by using theoretical transition energies. Effective fluorescence yields were determined with the aid of semiempirical ionization cross sections or relative Auger-electron and x-ray intensities.

The agreement with theory attained in these difficult, yet necessarily crude, experiments points toward the urgency of developing means for high-resolution x-ray and Auger-electron spectroscopy on systems of colliding atoms. Precise measurements and calculations of transition energies and intensities between multivacancy states must be carried out before the de-excitation of highly excited atoms can be understood in detail and before refined theories of ion-atom collision mechanisms can be put to the test.

The study of radiative transitions is making advances as significant as that of Auger processes. Energy levels and radiative decay rates of multiply ionized atoms are important for atomic-structure theory and in a variety of applications. Notably in astrophysics, such information is required to gain knowledge of the structure of stellar atmospheres and of the abundances of the elements. For this purpose, transitions must be identified and the associated oscillator strengths must be known. The latter can be determined by combining measurements of the mean life of the excited ionic state from which a transition originates with theoretical or experimental determinations of branching ratios to other states.

One of the most fruitful techniques for the measurement of oscillator strengths and radiative transition rates of highly ionized atoms has been beam-foil spectroscopy. This by now well-known technique involves the optical excitation and sometimes multiple ionization of an accelerated ion beam (usually in the high-keV to MeV range) traversing a thin foil (usually carbon, ~1000 Å thick or ~10 $\mu g/cm^2$).

As a result of the multiple atomic collisions of the ions during passage through the foil, a broad range of energy levels is populated, representing various degrees of ionization. States involving excitation of more than one atomic electron at a time are produced more easily in such a multiple-collision process in the foil than by other methods. The higher the ion-beam energy, the greater is the degree of ionization and excitation of a given atomic species.

Particularly important is the application of beam-foil spectroscopy to the study of forbidden transitions--magnetic dipole, electric and magnetic quadrupole, and higher multipoles. The intensity of such transitions increases with atomic number, their probability being given by terms in higher powers of αZ in the multipole expansion of the radiation field. Thus, the advent of heavy-ion accelerators of increasing energy promises to open additional regions for the exploration of forbidden transitions.

High energy is not necessary *per se* to conduct beam-foil spectroscopy; even such ions as Pb IV and Bi V have been studied at energies below 500 keV. Higher-energy machines, however, make few-electron atoms of larger atomic numbers accessible. Tandem Van de Graaffs have produced one- and two-electron ions of elements as heavy as Cl, and the Berkeley heavy-ion linear accelerator has permitted studies of forbidden decays in He-like Si, S, and Ar and of the Z-dependence of high-multipole radiative transitions. The Holifield Heavy-Ion Research Facility is expected to extend the range of such studies to elementary atomic systems of very high Z, including transition probabilities, the measurement of large radiative level shifts, and other experiments in strong-field electrodynamics that are of interest because relativistic and quantum-electrodynamic interactions can scale with high powers of Z (see Section II.C).

The beam-foil technique provides a natural method for measuring atomic lifetimes because of the impulsive excitation at the foil. One simply observes the exponential decay of a particular spectral line intensity as a function of distance ($x = vt$), downstream along the beam from the foil, to determine the mean life of the emitting state. To do this accurately requires a sufficiently high beam energy to prevent excessive energy loss and energy straggling in the foil, as well as small fractional beam-energy spread. These requirements make the Van de Graaff and tandem Van de Graaff accelerators commonly used by the last two generations of nuclear-structure physicists ideal for beam-foil spectroscopy lifetime studies. Such lifetime measurements are not restricted to resonance lines or excited ionic states that can be reached by electron or optical excitation. Furthermore, the ions are stripped and excited in one simple process as they pass through the foil.

The advantages of beam-foil spectroscopy are, however, offset by several experimental difficulties inherent in the technique. One of these is line-blending, caused by the simultaneous excitation of many states at once, often including two or more states of ionization. Another result of the rather indiscriminate beam-foil excitation process is competition between the spontaneous decay of the state under study and the continued feeding of the state by cascade transitions from higher levels. Cascade excitation thus gives rise to a time (and distance) dependence of the light intensity that is often not a simple exponential, causing complications in the lifetime measurements. A velocity correction is required for energy loss when the ion beam passes through the foil, particularly for low-energy beams; hence an independent measurement of foil thickness or final beam velocity is necessary. Furthermore, foil characteristics do change with time, limiting the statistical accuracy that can be obtained in practice.

In spite of the problems associated with the beam-foil spectroscopy technique, it is appealing because of its relative simplicity and wide applicability. The usefulness of beam-foil measurements of oscillator strengths is strikingly illustrated by one example of their application to the determination of elemental abundances in astronomical sources, viz., that of iron in the sun. Beam-foil studies have led to an upward revision of the abundance of iron in the solar photosphere, by approximately one order of magnitude. On the assumption that this enhancement in the iron abundance pertains to all solar matter, an increase in solar opacity is implied, which demands an increase in the central temperature to account for the observed solar flux. This higher temperature affects the thermonuclear reaction rates that are presumed to generate the sun's energy, in such a way that the neutrino flux expected at the earth is five or more times greater than the measured upper limit. The solar neutrino mystery constitutes a major scientific crisis; its link with inner-shell atomic physics is interesting to note in the context of this report.

Ion-atom collisions produce excited atomic systems that decay by unusual radiative transitions that are not confined to high multipolarities but also include energy-shifted lines, which are analogous to satellite lines of traditional spectroscopy. The shifts of characteristic x rays emitted in ion-atom collisions can reveal the charge state of the emitter; it can be anticipated that sometime in the future sufficiently high spectroscopic resolution may be attained to characterize the actual multiplet state of the radiating ion.

An interesting curiosity has been the observation of K "hypersatellites" emitted when one outer electron makes a transition to a totally vacant $1s$ shell; the shift of the hypersatellite with respect to the diagram line provides a measure of the extent to which a K electron screens the nucleus. A fascinating effect, just discovered, is the emission of a single photon as *two* electrons fill an empty K shell. Rare processes of this nature can provide sensitive tests of theory, particularly with regard to electron correlations.

A most extreme shift of x-ray energies occurs when colliding atoms approach to within the "united atom limit," with the electrons of target and projectile moving in a quasimolecular potential produced by nuclei that coalesce on a scale of atomic distances. X rays have indeed been studied that are characteristic of the energy-level separations of molecular orbitals, and continuous x-ray spectra have been measured that can be attributed to well-characterized time-dependent quasiomolecular systems. The study of such radiation has become of particular interest in connection with the exploration of ion-atom collision mechanisms (see Section I) and in view of the possibility of producing superheavy molecules in heavy-ion collisions.

Pulsed and continuous-wave laser excitation of specific excited states in fast ion and atom beams is a new and rapidly growing part of accelerator-related atomic physics. Cascade-free excitation measurements, studies of the Lamb shift in high-Z hydrogenic ions, and precision second-order Doppler-shift measurements are examples of current research.

B. Production and Decay of Metastable Atoms

Atoms in an accelerator-produced beam can be stripped down to a few electrons by placing a thin foil in the beam path. The emerging few-electron atoms can exist in certain metastable states. The decay of metastable foil-excited ions can be observed, downstream from the foil, by detecting the emission of characteristic x rays or Auger electrons. Thus lifetimes of the order of nanoseconds or less can be measured by time of flight, because the ion velocity is generally of the order of 10^9 cm/sec. Measurements of these lifetimes, or transition rates, are of interest in fundamental theory, because the long-lived metastable states cannot decay by electric dipole radiation but only by transitions that arise from higher-order terms in the Hamiltonian (spin-spin interaction, spin-orbit interaction) or from higher multipoles (e.g., magnetic dipole or electric quadrupole radiation). Thus, measured transition rates can serve to test theoretical approaches to the treatment of terms that contribute little in allowed transitions (see also Sections II.A and II.C).

Practical interest in the decay of metastable atomic levels has been heightened by the observation of such transitions in stellar atmospheres. The temperature of the corona of the sun has been calculated from the observed intensities of the 1.5-nsec 21.8-Å 2^3P_1-1^1S_0 transition in O^{6+} and the magnetic-dipole 2^3S_1-1^1S_0 line, compared with the allowed 2^1P_1-1^1S_0 line.

The emission of keV-energy electrons from metastable autoionizing states of few-electron atoms in highly stripped beams has only recently been observed. Because of selection rules against Coulomb autoionization, the quartet states of the lithiumlike isoelectronic sequence, for example, are metastable and decay only due to spin-orbit and spin-spin interactions. High-resolution electron spectra from the decay of these states have now been measured, and transition rates have been determined from decay-length measurements in stripped ion beams.

Photon and electron spectra from beams of metastable atoms are likely to be the subject of widespread investigation for some time to come.

The excitation time in foil stripping, no longer than the transit time of the ions through the foil, is of the order of 10^{-15} sec. It follows, by the uncertainty principle, that levels with energy separations of ~1 eV can be coherently excited. Such coherence manifests itself through an oscillatory time dependence of the intensity of the optical radiation emitted from the beam at a particular angle; this time dependence is transformed into a spatial oscillation of light intensity as a function of distance downstream from the point of excitation. Measurements of these "quantum beats" can lead to a determination of the energy separations of fine and hyperfine levels of ions.

Collision-induced alignment and orientation effects are currently under intensive study, using both normal and oblique incidence of the ion beam upon the foil and including the application of external fields. Aside from their intrinsic interest, such effects aid in the identification of spectral lines through the determination of atomic g factors.

C. Tests of Fundamental Theory

The ability to produce highly stripped one- and two-electron ions in accelerator beams entails an opportunity for conducting new experimental tests of fundamental physical theory, mainly of quantum electrodynamics (QED). Such tests will be of particular importance in connection with an understanding of the atomic properties expected of superheavy elements.

Precision tests of QED under new conditions of strong Coulomb fields in hydrogenic heavy ions are currently being undertaken in several laboratories. A 1 percent measurement of the Lamb shift in hydrogenic ions with a nuclear charge $Z > 8$ is sensitive to the important vacuum polarization term. One difficulty, however, is caused by the finite size of the nucleus. If new effects or discrepancies from theory are discovered with heavy-ion beams, then interpretation of the Lamb-shift measurements will probably require better values for the pertinent nuclear radii, to be derived from electron-scattering of muonic-atom experiments.

Heliumlike and lithiumlike heavy ions are also of great interest, and their spectroscopy promises to be valuable in testing highly accurate relativistic calculations of atomic wavefunctions. With heliumlike as with hydrogenic ions, important tests of basic theory can be conducted; precision measurements of the fine structure of the 2^3P states, for example, can be used to test relativistic and QED effects.

In summary, our fundamental understanding of relativistic atomic structure and of QED can be tested, with the use of highly stripped ion beams, under novel conditions where the Coulomb field is much stronger and relativistic effects play a major role rather than constituting only a small perturbation.

III. INTERFACE WITH NUCLEAR AND SOLID-STATE PHYSICS

Historically, application of the techniques of nuclear physics has led to the current high level of activity in atomic-collision physics explored with keV and MeV charged-particle beams. The connection between nuclear and atomic physics runs much deeper though, because all nuclear collision processes necessarily take place in an atomic environment. The systematic exploration of the interface between atomic and nuclear physics is just beginning, and interesting results can be expected.

Because of the small size of the nucleus in comparison with atomic shells, and the disparity in interaction energies, it has usually been possible to ignore the electron "coterie" in the interpretation of nuclear-physics experiments, except as a source of systematic influences that must be taken into account in the reduction of data. The close connection between the two fields is exemplified by the effect of atomic energy-loss processes on nuclear observations, as in the case of the "Lewis effect," which appears in certain thick-target measurements of narrow nuclear resonances. Similarly, in the correct identification of decay products, it is essential to distinguish photons and electrons that are signatures of a nuclear reaction from those of purely atomic origin, created from impact of the same beam.

It was recognized long ago that, with increasing refinements in nuclear experimentation, it would become necessary to think of the target in a nuclear collision experiment, not as an isolated nucleus in an inert atomic environment but as an atom with a nucleus at its center, taking into account the dynamic changes that take place in the atom during the course of the collision. Excitation and ionization of the target atom during a nuclear reaction become important in high-resolution measurements. Although energetically these effects tend to be small, the much longer range of atomic interactions partially compensates for their relative weakness. The structure of the atom is subject to excitation by an impinging nuclear particle, through recoil of the target nucleus or merely because the charge of the target nucleus is suddenly changed. Because of recoil, even reactions involving neutrons can show atomic effects.

Several manifestations of these atomic effects can emerge in nuclear experiments. Measurements of sharp nuclear energy levels in compound nuclei can be affected, as can the lifetimes of excited states. The precise determination of nuclear masses requires a fuller understanding of the changes in the surrounding atoms. With nuclear-physics experiments approaching a level of resolution (~100 eV) comparable to atomic energy differences, one can anticipate the observation of additional atomic effects influencing such nuclear properties as the positions, widths, and shapes of resonances.

Conversely, nuclear phenomena can be used as experimentally observable flags signaling that a "direct hit" has occurred in the encounter between an incident ion and an atom, permitting the study of inelastic atomic collisions initiated by projectiles that traverse the atom head-on.

The slowing down of fast charged particles traversing matter is one of the few fields of experimentation on fundamentally atomic processes that has traditionally been pursued with vigor in accelerator laboratories dedicated to nuclear physics. The reasons were practical, because an understanding of the stopping of charged particles in targets is essential to the interpretation of many nuclear-physics experiments. Measurements of stopping powers and particle ranges are, to be sure, only indirectly related to the binary collisions between ions and atoms with which the present report primarily deals. Such quantitites as average energy losses, straggling widths, and the details of the energy distribution of secondary electrons emitted in the passage of an ion through matter are statistical entities, in principle derivable from the underlying cross sections for collisions with single atoms. The route of calculating these averages *ab initio* from the basic cross sections--even if these were precisely known--is as yet far too arduous and undependable, however, so that accurate direct experimental determinations of the parameters governing the slowing down of ions remain important tasks for accelerator laboratories.

The subject is still very much in flux. For example, the stopping power for heavy particles has been assumed to be strictly proportional to the particle velocity in the low-velocity region, below the stopping-power maximum. Theoretical estimates based on this assumption have been incorporated into computer codes used in various laboratories. Recent data, however, suggest that this assumption of velocity proportionality may be introducing serious errors in range estimates for heavy ions at low velocities. Experiments on slow Br, I, and U ions indicate that stopping power may be expressed better by a semiempirical relation of the form $dE/dx = a + bv$. Attempts to find the exact form of this function are in progress. The problem calls for much additional research, because of the importance of the slowing down of heavy ions in many contexts.

The study of atomic collisions in solids has been greatly aided by the discovery and applications of the phenomenon of *channeling*. When an ion enters a crystalline solid at a small angle with respect to atomic rows or planes, it undergoes a set of correlated small-angle scattering events with the closely spaced atoms, which tend to steer the ion's trajectory away from close collisions with lattice atoms. The potential that determines the motion of the ion can be viewed as continuous and as made up of an orderly sum of the individual ion-atom potentials. Under these conditions the ion is said to be channeled. Experimental conditions are easily achieved under which more than 90 percent of all ions entering a crystal are channeled.

The channeling effect has several important consequences.

1. Collision phenomena are suppressed that involve small impact parameters, such as nuclear reactions, Rutherford scattering, inner-shell ionization, and atomic displacements (nuclear stopping).

2. If channeling occurs between two planes (sheets) of atoms in a crystal, the simple two-dimensional potential leads to discrete oscillatory trajectories for the channeled ions; these can be identified by a characteristic energy loss produced by the regions of electron density encountered along the ion's path.

3. Particles injected with low transverse momenta, corresponding to an energy below the potential barrier between atomic rows, can be used to map interatomic potentials out to valence-electron distances (hyperchanneling).

4. Highly stripped high-velocity ions sweeping down the center of a channel encounter only valence or conduction electrons that move at relatively low velocities; then the atomic encounters are similar to those arising in a dense electron gas.

The first of these effects (reduction in nuclear reactions and Rutherford scattering) has been extensively used to locate impurity atoms in a host lattice. The method is applied in the analysis of ion-implanted solid-state devices and is used extensively in the analysis of ion-bombarded surfaces; several accelerators are now specifically dedicated to this work.

The second and third effects have been used to determine interatomic potentials and impact-parameter-dependent inelastic losses for ions ranging from 0.5-MeV protons to 60-MeV iodine. The use of center-channel electrons to simulate interactions between ions and an electron gas has been demonstrated in several ways. It was found that charge-capture and -loss cross sections for such ions as

2-MeV/nucleon O^{7+} and O^{8+} in the center channel were strongly reduced because the electrons that could be captured have low velocities; crystals that are 1000 atoms thick act as thin targets for charge exchange. Measurements of the energy loss of ions that do not undergo charge exchange can reveal the relationship between stopping power and the ion charge state; radiative capture by the ions can be related to the energy distribution of the electrons in the channel. These observations indicate the applicability of such accelerator-based experiments to studies of the interactions between electrons and highly stripped ions, such as occur in CTR plasmas.

As an example of research that touches on both nuclear and solid-state physics, an interesting technique for the measurement of extremely short nuclear lifetimes on the basis of channeling deserves mention. If a nucleus in a string of atoms is struck by an incoming ion and has time to move out of the string before de-exciting by particle emission, then the emitted particle is free to emerge alongside the string. If, however, the nuclear excited state has so short a mean life that there is no time for the struck atom to move out of its row, then emission of the particle in the direction of the string is blocked. For velocities of $\sim 10^9$ cm/sec and string thicknesses as small as 0.1 Å, this "channel-blocking technique" can serve, in principle, to measure half-lives of the order of 10^{-18} sec.

IV. AN APPLICATION: PARTICLE-INDUCED X-RAY FLUORESCENCE ANALYSIS

A useful application of particle accelerators has been made to the excitation of characteristic x rays for trace-element analysis. Until about 1970, x-ray fluorescence analysis was generally performed by photoionizing samples with radiation from a conventional x-ray tube; the fluorescent radiation was analyzed with crystal-diffraction spectrometers (wavelength dispersion). The development of lithium-drifted silicon detectors with good energy resolution made it possible to analyze the fluorescent x rays in a multichannel mode (energy dispersion).

The sensitivity and usefulness of the energy-dispersive method coupled with fluorescent excitation by a beam of energetic protons was dramatically demonstrated by a group of Swedish investigators in 1970. It was shown that many elements can be detected simultaneously at a level as low as 10^{-12} g. A flurry of activity in the United States followed this demonstration as groups at many accelerator laboratories began to look for trace elements in a wide variety of environmental and biological samples. The technique made it relatively simple to determine simultaneously and quantitatively the presence of a number of trace elements down to a few parts per million; this capability was particularly welcome as interest in environmental and pollution problems became intense. In more than a dozen laboratories, experiments were then initiated on charged-particle x-ray fluorescence analysis.

Following the initial efforts, much work was done on target preparation, reproducibility checks, verification of quantitative aspects by use of standards, and determination of optimum particle types and energy. Protons with an energy of a few MeV were found to give best results; with heavier ions, excitation cross sections are greater but the signal-to-background ratio suffers, mainly because of increased bremsstrahlung from secondary electrons.

The greatest precision in x-ray fluorescence analysis can still be attained with Bragg spectrometers. Such spectrometers may have a tenfold better resolution than Si(Li) detectors, which improves the signal-to-background ratio markedly and helps greatly in the proper identification of trace elements. On the other hand, crystal spectrometers suffer from the disadvantage of being single-channel devices; solid-state detectors permit the simultaneous observation of an entire spectrum. Multiple crystal spectrometers overcome this disadvantage to some extent; there are commercial units employing 24 spectrometers, all measuring x rays from the same target. With such apparatus, counting-rate problems are less severe than with solid-state detectors, and data can be collected rapidly. Major disadvantages are the cost (around $100,000), the limited number of channels, and the need for high-intensity excitation.

As a means of exciting x rays, the bombardment with charged particles competes with the more traditional approaches. Radioactive sources emitting monoenergetic photons lead to a good signal-to-background ratio but generally require long analysis times, because source strengths are limited in practice. Conventional x-ray tubes are relatively low in cost and simple to maintain, compared with particle accelerators. The general result of studies comparing charged-particle and x-ray excitation is that the quality (sensitivity) and quantity of data that can be obtained by the two methods are not drastically different and that charged-particle excitation is but one possible way of producing fluorescent x rays. There appears to be some preference for charged-particle excitation in the analysis of light trace elements ($Z < 23$) and for x-ray excitation if heavier elements are sought. An exact comparison of the two methods is difficult, because of such variables as sample matrix structure, the use of absorbers in the primary x-ray beam and of x-ray fluorescers, and target heating under charged-particle bombardment.

In summary, trace-element analysis by charged-particle excitation is not likely to replace the more conventional and more economical x-ray excitation. There are, however, a number of laboratories that have Van de Graaff accelerators of suitable energy, multichannel pulse-height analyzers, and other needed equipment so that x-ray fluorescence analysis can be carried out with little development work and little capital expenditure.

The developments in x-ray fluorescence analysis in the past five years are perhaps most noteworthy for realization of the great importance of trace elements in the environment and in a variety of medical problems. From the unsuspected presence of cadmium in ashed alpine plants to a noticeable deficiency of rubidium in the muscle tissue of patients on hermodialysis (with artificial kidney machines), there have been surprises and some satisfying insights into long-term problems. To a large extent, these new and exciting results have come from the use of the broad-range feature of the energy-dispersive x-ray fluorescence method, often in association with charged-particle excitation. Even more important has been the enthusiasm and imagination of people in accelerator laboratories who have become involved in trace-element analysis.

3 CURRENT RESEARCH EFFORT

Research in fundamental atomic physics employing accelerators and other large machines is a new field of endeavor. It has not yet been generally recognized as being in a separate domain, yet its characteristics and requirements set it off quite distinctly from such fields as traditional atomic spectroscopy, nuclear physics, and plasma physics, albeit funding is often provided under one of these other categories. A main purpose of this report is to describe inner-shell atomic physics as a separate subdiscipline and to indicate what is being done and what can be done in this field.

The current literature provides an indication of the relative level of activity in the field. Table 1 shows the percentage of papers that pertain to collisions of accelerated ions with atoms among articles published during 1972-1974 in four leading physics journals. In Table 2, we list the number of papers on inner-shell atomic physics contributed to the biennial International Conference on the Physics of Electronic and Atomic Collisions. In addition to the contributed papers indicated in Table 2, 14 of the 62 invited papers at the 1975 Conference dealt with inner-shell atomic physics.

A survey was conducted by the panel to determine what facilities in the United States are being used for, or are scheduled for, atomic physics research. In response to approximately 120 questionnaires (see Appendix C) sent out in July and November 1974, we received replies from 72 laboratories. In 42 of these, accelerators are now used for atomic physics research, and 6 additional laboratories maintain active programs using accelerators elsewhere (see Appendix D). In 4 laboratories, atomic physics research with ion accelerators is planned within one year, and in 3 others, after more than one year.

TABLE 1 Published Articles on Collisions of Accelerated Ions with Atoms

Journal	Year 1972	1973	1974	1972-1974
J. Phys. B	14%	20%	15%	16.3%
	33/235	52/264	38/254	123/753
Lett. J. Phys. B	15%	16%	21%	17.8%
	12/81	18/111	29/139	59/331
Phys. Rev. A	10%	14%	16%	13.3%
	66/667	97/707	102/649	265/2023
Phys. Rev. Lett.[a]	22%	28%	18%	22.5%
	33/153	35/124	24/132	92/409
All four journals	12.7%	16.7%	16.4%	15.3%
	144/1136	202/1206	193/1174	539/3516

[a] Atoms, molecules, and related topics, and atoms in matter.

TABLE 2 Papers that Involve ≥100-keV Accelerators or Synchrotron Radiation Sources, Contributed to the International Conference on the Physics of Electronic and Atomic Collisions, 1969-1975

Meeting	Papers/Total	Percentage (%)
VI ICPEAC (Cambridge, Mass., 1969)	22/367	6.0
VII ICPEAC (Amsterdam, 1971)	29/457	6.3
VIII ICPEAC (Belgrade, 1973)	38/446	8.5
IX ICPEAC (Seattle, 1975)	77/567	13.6

TABLE 3 Ion Accelerators (≥100 kV) Used for Research in Atomic Physics in the United State[a]

Van de Graaffs		49
Including Multistage	14	
5-MV	7	
2- to <5-MV	21	
<2-MV	7	
Dynamitrons		3
Cyclotrons		4
Small accelerators (≥100 kV)		11
Including Cockcroft-Waltons	4	
Heavy-ion linear accelerators		2
TOTAL		69

[a]Data based on a questionnaire survey conducted by the Ad Hoc Panel on Accelerator-Related Atomic Physics Research.

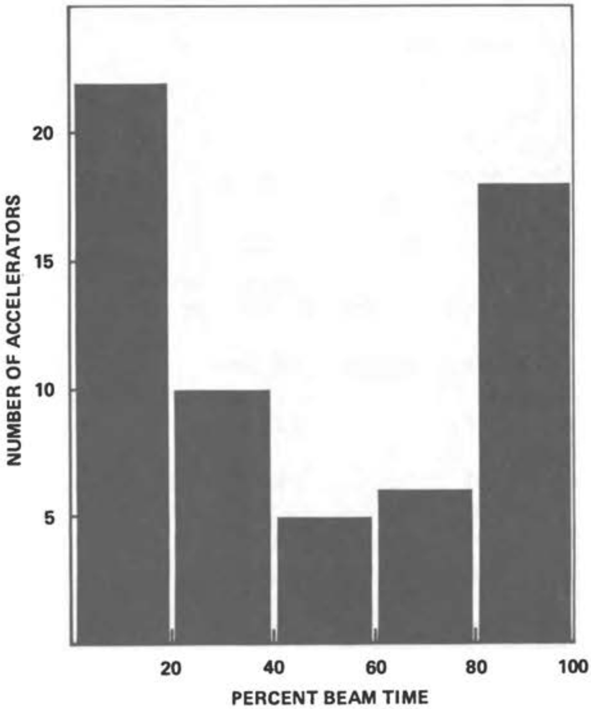

FIGURE 1 Percentage of accelerator beam time devoted to atomic physics. (Based on survey by the panel.)

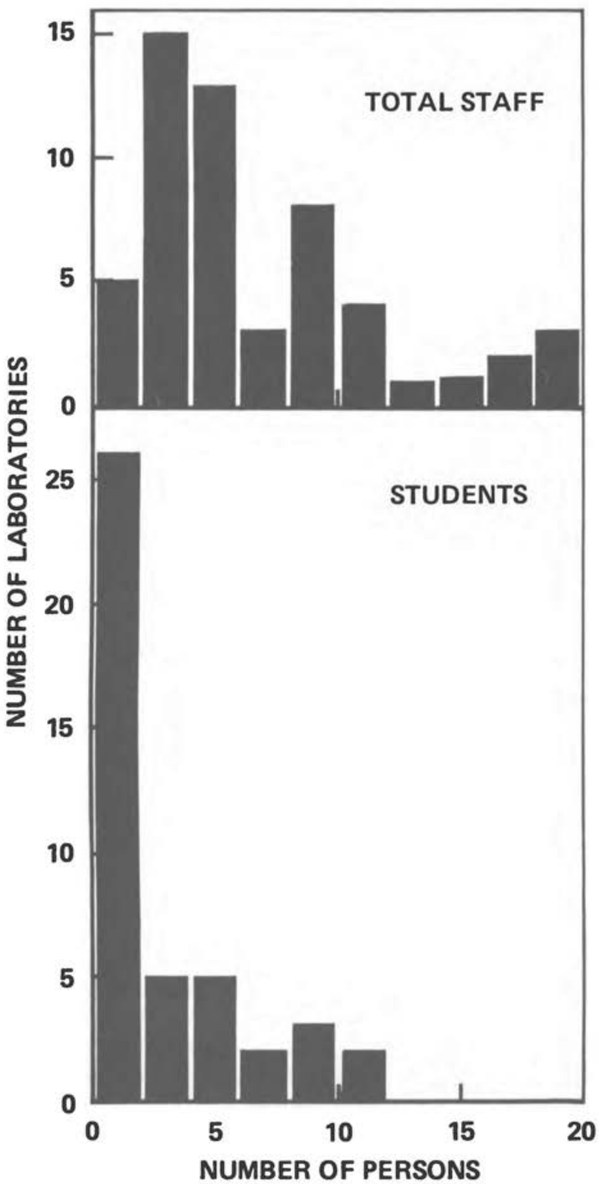

FIGURE 2 Total scientific staff and number of students in accelerator-related atomic physics groups that responded to panel questionnaire.

More Van de Graaffs are used for atomic research than any other kind of accelerator (Table 3), but cyclotrons, Cockcroft-Walton machines, Dynamitrons, and linear accelerators are also employed.

Beam time devoted to atomic physics ranges from <10 percent on 11 machines to 100 percent on 16 accelerators (Figure 1). Although this latter group of "dedicated" machines comprises mostly smaller accelerators, it does include some Van de Graaffs of up to 5.5 MV.

Three hundred and ninety-one investigators are involved in the research covered by the survey; this figure includes 142 graduate students and 2 undergraduates. In only 13 laboratories (27 percent) are no students participating in atomic research on accelerators. Scientific personnel ranges from 1 to 20 per group; however, most groups are small (Figure 2), with a median of 6 investigators. The number of graduate students ranges from 0 to 11 per group, with 3 the median.

Funding reported by the surveyed groups is mostly from the Energy Research and Development Administration (21 laboratories) and the National Science Foundation (17); others receive support from the Office of Naval Research (6), the Air Force Office of Scientific Research (3), the National Aeronautics and Space Administration (3), the Environmental Protection Agency (3), the Welch Foundation (3), and the Army Research Office-Durham (2); 19 groups reported that they rely on internal funding.

4 PERSPECTIVES AND APPLICATIONS

The fields of investigation summarized in this report contain some major unsolved problems and challenges in atomic physics. Furthermore, there are instances in which significant applications of fundamental atomic physics research can be made in other disciplines and in technology.

We are currently entering a new phase in the study of fundamental interactions involving electrons, heavy ions, and photons. The use of high-speed computers now makes it possible to apply to atomic physics the complex formalism of collision theory that has evolved since the 1930's. Until recently, detailed comparison between theory and experiment was only possible in the restricted domain of the collisions of protons or electrons with hydrogen. Continued development of sophisticated computational techniques, however, is gradually extending the range of possible comparisons to increasingly heavier systems. It remains to be seen whether the presently available theoretical formalism will be sufficient to describe heavy-particle collisions consistently or whether fundamentally new approaches will be necessary. Experiments with few-electron systems are being performed in which the interactions are well understood and the formulation of quantitative theoretical predictions will be possible when the best computational techniques are employed. But there are cases in which experiments are getting ahead of basic theory. In some fundamental interactions now being studied experimentally, transition probabilities approaching unity are being revealed. Because much of the present theoretical formalism is based on perturbation techniques, it is a challenge to develop the proper theoretical approaches that can be used to describe such phenomena.

Research in fundamental inner-shell atomic physics is directed toward an understanding of binary collision processes that leads to the capability of calculating such essential ingredients as cross sections, transition rates, and excited-state populations needed to treat the behavior of more complex systems. For example, aspects of collision phenomena in solid materials, with concomitant technological applications, can be determined by estimating the cumulative effect of the complicated binary atomic collisions that occur during slowing down. Another application of fundamental knowledge of binary processes is to neutron-induced damage in reactor environments. The energy of a slow neutron traversing matter is dissipated in producing bulk lattice damage almost entirely through atom-atom and ion-atom collisions. The effects of such neutron damage can be simulated by bombardment with high-energy protons or with heavy ions in the energy range from a few eV to tens of MeV. Yet another application of binary collision theory is related to the development of sources of highly stripped ion beams for injection into high-energy heavy-ion accelerators. Estimates of the intensities of highly charged ions that may be attainable through multiple-collision processes can be made by considering the cumulative results from binary collisions.

Significant overlap with other scientific disciplines characterizes fundamental studies of atomic states that are produced at collision velocities comparable with the electron orbital velocity. From nuclear physics, the need to interpret atomic effects provided the initial stimulus for accelerator-related atomic-collision studies. The knowledge gained from atomic studies of heavy ions is now being applied to the investigation of fundamental nuclear properties. For example, the interaction of nuclear moments of atoms recoiling in vacuum with atomic $1s$-vacancy states has been used to determine nuclear g factors.

In solid-state physics, knowledge of lattice site location, radiation damage, surface states, and interatomic potentials has been gained through applications of ion-atom collision studies. Contributions from low-energy atomic scattering have led to further understanding of the dynamics of chemical reactions and of important processes in aeronomy. Higher-energy atomic collisions lead to similar insights into astrophysical processes that involve highly ionized species. Furthermore, inner-shell ionization appears to be an important nonthermal ionization process in the interstellar medium.

Numerous applications of low-energy collision processes have been found in the development of lasers. Devising lasers of higher energy is one of the foremost current challenges in applied physics, and it is not impossible that a successful x-ray laser scheme may involve some of the inner-shell metastable states that are produced abundantly in high energy atomic collisions. Such states constitute an important way of storing a large amount of energy in a single atom for protracted periods. Little is known about the production mechanisms for inner-shell metastable states. Spectroscopic studies have been carried out to identify multiplet states of various configurations and to measure lifetimes along isoelectronic sequences. It has been speculated that the creation of these metastable states involves multiple events. Extensive fundamental studies of the production and quenching processes of long-lived few-electron excited states will be required before any concrete applications of ion beams with inverted populations can be undertaken.

An urgent need for a variety of inner-shell atomic physics data has arisen in connection with the controlled thermonuclear reaction (CTR) program. The problem has been identified in a report of the Research Panel on Atomic, Molecular, and Nuclear Physics in CTR (see Appendix D). The panel points out, for example, that the most serious immediate threat to the satisfactory operation of Tokamak-type machines appears to arise from contamination of the plasma by heavy ions such as W or Au. Densities of such elements as W or Au in excess of 10^{11} cm^{-3} in Tokamak-type reactors will extinguish the reaction by recombination alone. High priority is therefore recommended for research on the identification of strong resonance lines for highly ionized, heavy elements, including the Cu and Zn isoelectronic sequences all the way to the upper end of the periodic table. Systematic investigation of the atomic structure of the first 40 states of ionization of W and Au is called for. The transition probabilities for resonance lines in such ions will have to be determined to permit quantitative measurements of impurity concentrations and predictions of radiation intensities and power loss. Of further importance in plasma diagnostics is the determination of the energy shifts of K and L x rays from multiply ionized atoms, as compared with normal atoms; charge-state distributions could then be deduced from observed x-ray spectra. Knowledge of transition probabilities in multiply ionized O, C, and N is needed because these ions constitute abundant impurities in CTR plasmas, influence the plasma behavior, and may serve as probes for plasma diagnostics. Other needs include electron excitation cross sections for multiply ionized atomic species, charge-exchange cross sections, and information on radiative recombination of heavy atoms in all states of ionization in plasmas up to electron temperatures of ~100 keV.

In materials research, analytical techniques have been developed that employ secondary-ion mass spectrometry, ion-induced x rays, and ion backscattering. When used in conjunction, ion-induced x rays and ion backscattering permit determinations of depth profiles of impurity concentrations; such profiles cannot be obtained by any other analytical methods. The usefulness on ion beams in this application is, however, restricted to selected cases.

In conclusion, it should be pointed out that in the training of students, accelerator-related atomic physics provides expertise that equips young physicists well for transfer to industry and to government laboratories. Detection techniques and logic requirements in experimental inner-shell atomic physics demand familiarity with complex and sophisticated electronic devices and modern computing equipment. Students are exposed to the use of a broad range of instrumentation and experimental techniques, including applications of vacuum technology, computer-regulated control circuits, ion-beam optics, and ion-source development. Studies of few-electron species in atomic collisions provide close integration between experiment and theory of the time evolution of a few well-understood states, so that early in their training students can gain insight into fundamental theoretical concepts of quantum mechanics.

In addition to these conclusions on the potential and applications of accelerator-related atomic physics research, the Panel formulated a set of recommendations based on its survey and study. These recommendations appear in the Summary at the beginning of the report in the section titled "Findings and Recommendations."

APPENDIX A
Atomic Research with Large Plasma Devices and Other Unique Facilities

Although the main thrust of this report is directed toward the present and potential uses of ion accelerators for research in inner-shell atomic physics, it is pertinent to consider briefly the possibilities that some other types of machines hold for such research.

Of considerable interest in this context are devices that have been or may be constructed for controlled thermonuclear research. Facilities at the Lawrence Berkeley Laboratory, for example, will provide for heavy elements in high charge states beyond those that have been studied heretofore. In these systems, foils with atomic number ranging from 40 to 80 are irradiated by intense laser sources, generating high-Z ions. X-ray emissions from these ions range from a few hundred electron volts to ~10 keV and are rich in satellite lines of every conceivable combination.

Theta pinches with densities in the vicinity of 10^{16} cm^{-3} can produce electron temperatures of ~1 keV for some 10 μsec and are capable of completely stripping intermediate-Z atoms when added in 1 percent fractions to the discharge. In addition, Tokamaks, even of modest size, operating at densities between 10^{12} and 10^{13} cm^{-3}, can produce electron temperatures up to 2 keV on a scale of 10 msec, providing similar stripping of intermediate-Z atoms, as well as significant new spectral data from atoms of higher atomic number. The Los Alamos Scientific Laboratory operates an intermediate-sized theta pinch devoted almost entirely to the study of oscillator strengths and opacities. A group at the Princeton Plasma Physics Laboratory deals with spectroscopic aspects of its Tokamak.

The Oak Ridge National Laboratory has two large plasma devices that are applicable to atomic physics studies, although at present they are being used almost exclusively for plasma physics experiments. One of these is ORMAK, a pulsed toroidal plasma of the Tokamak class. The other, called the EBT plasma, is a dc toroidal device composed of mirror coils arranged in a torus, providing a bumpy magnetic field. The electron density in the ORMAK is $\sim 3 \times 10^{13}$ cm^{-3}, and in the EBT, $(1\text{-}2) \times 10^{12}$ cm^{-3}; electron temperatures attained are 800-1000 eV and 0.1-1.0 MeV, respectively.

High-current neutral beam sources are being developed under the CTR program, for injection across magnetic fields. These devices can supply a large variety of atoms in highly excited states.

The construction of an electron-ring ion trap for the production of high-charge-state ions, with associated spectroscopic instrumentation for research in the physics of highly ionized atoms, has been proposed at the Lawrence Berkeley Laboratory. This facility would be used with the existing LBL electron linear accelerator, for such experiments as measurements of emission spectra from 40- to 50-fold ionized heavy atoms, studies of the production of such ions by multiple successive impact of relativistic electrons, measurements of their neutralization by electron pickup from neutral gas, and work on other collisional and radiative processes. Also proposed are tests of quantum electrodynamics by measuring the $2^2P_{3/2,1/2}-1^2S_{1/2}$ energy separations in high-Z hydrogenlike ions and the fine structure of the 2^3P states of He-like ions.

Finally, a list of unique major facilities for research in atomic physics would be incomplete without some additional items: Telescopes (radio, infrared, optical, ultraviolet) allow the study of atoms and molecules under conditions that cannot be realized on earth. High-altitude vehicles, space vehicles, and Skylab provide unique opportunities. Large computers make the solution of increasingly complicated atomic problems feasible. Large-scale spectrographic equipment exists at the National Bureau of Standards and at various other laboratories; this apparatus, uniquely suited for studies ranging from the infrared to the vacuum ultraviolet, could be used part-time by outside investigators, under suitable circumstances.

The possibilities of atomic research with intense monochromatic gamma rays from nuclear reactors deserve exploration. The extraordinary radiation flux from exploding nuclear devices may permit some unique experiments. Atomic experiments could be done in the high magnetic fields of the National Magnet Laboratory and in ultrahigh transient megagauss fields produced by implosive methods. Some of these suggestions are speculative, but they serve to indicate how great the potential is for less conventional types of atomic research.

APPENDIX B
Research Opportunities with Synchrotron Radiation

The use of synchrotron radiation to study the interaction of radiation with matter is currently expanding rapidly on a worldwide scale. Synchrotron radiation has characteristics that make it a unique experimental tool: the intensity is high over a broad spectral range and the energy can be tuned with the use of monochromators; the radiation is highly polarized, has a sharply pulsed time structure, and is in an ultrahigh vacuum environment. Morevoer, synchrotron radiation from storage rings (rather than from synchrotrons) is exceedingly stable in space and time.

In the United States, there are currently two national synchrotron-radiation facilities that employ storage rings: the 240-MeV Tantalus I at the Synchrotron Radiation Center in the Physical Sciences Laboratory of the University of Wisconsin and the ~4-GeV ring SPEAR at the Stanford Synchrotron Radiation Project (SSRP). The Wisconsin facility is "dedicated," that is, it is used exclusively for research with synchrotron radiation; the Stanford project is "symbiotic," sharing the storage ring SPEAR with users who conduct colliding-beam particle-physics experiments. The National Bureau of Standards (NBS) operates a Synchrotron-Ultraviolet Radiation Facility (SURF), primarily for in-house research; a ~300-MeV storage ring is nearing completion at NBS. Research in high-energy (≥40-keV) synchrotron radiation is furthermore being initiated at the Cornell University 12-GeV electron synchrotron.

Both SSRP and the Wisconsin Radiation Center are national facilities, supported by the National Science Foundation (NSF) to serve all qualified investigators. The SSRP became operational in 1974; it provides U.S. scientists with a tuneable ultraviolet source in the vacuum region from 30 eV up to (presently) ~500 eV. At the other end of the spectrum, SSRP has a conveniently tuneable source of x rays in the 3- to 20-keV region. The Wisconsin Radiation Center has been in operation for seven years, with research programs in the vacuum ultraviolet and soft x-ray region.

Synchrotron radiation facilities are actively being developed abroad. Both DESY in Hamburg and the Daresbury Nuclear Physics Laboratory in England have extracted focused x-ray beams similar to SSRP, but these suffer from not having storage-ring sources with high beam stability. At DESY, however, a large storage ring facility named DORIS has become operational; this is potentially more powerful than SPEAR and will soon be used for synchrotron radiation experiments. At Daresbury, a 2-GeV electron storage ring to be called NINA II is under construction; capable of eventually handling beams up to 1 A in intensity, the ring will serve as a dedicated synchrotron radiation source. A 1.8-GeV storage-ring synchrotron radiation source DCI is under construction at Orsay. Japan operates the 1.3-GeV synchrotron INS-SOR I and has tested a dedicated 300-MeV storage ring INS-SOR II. Synchrotron radiation facilities in the Soviet Union include the 6.0-GeV accelerator ARUS at Yerevan and a 1.3-GeV synchrotron and storage ring under construction at Krasnaja Pachra near Moscow. Italy has proposed the 12-GeV storage ring facility SUPER-ADONE at Frascati, and the installation of two photon lines on the existing 1.5-GeV ADONE has been authorized.

In many fields of research, synchrotron radiation offers substantial advantages over radiation from other sources; we note a few examples related to atomic physics. In the x-ray region, synchrotron radiation (that can be monochromatized to better than 0.1 eV at 8 keV) permits extremely high-resolution x-ray photoelectron spectroscopy; the time structure of the radiation has made it possible to measure photoelectron energies by time-of-flight techniques. Tuneable photoabsorption spectroscopy permits studies of absorption edges and has led to the rapid resurgence of a technique called EXAFS, based on the measurement of extended x-ray absorption fine structure. This technique constitutes a powerful method for obtaining local structural information in complex solid-state, chemical, and biological systems. Both elastic scattering (elastic diffraction and thermal diffuse) and inelastic scattering measurements (Compton, resonant, and nonlinear scattering) can be carried out with great advantage using synchrotron radiation. High-intensity small-angle scattering studies are possible with recent improvements in focusing monochromators. The feasibility of x-ray holography with synchrotron radiation is actively under study, and the possibility of making an x-ray microscope with such a source has already been demonstrated.

Also in the ultraviolet, vacuum-ultraviolet, and soft x-ray spectral range, synchrotron radiation offers unique advantages for the study of atomic structure and of the electronic structure of matter. The most numerous applications are to solid-state physics, but atomic and molecular physics benefits from the possibility of experiments in photoabsorption spectroscopy, photodissociation, and photoionization spectroscopy. Such topics as the electronic and vibrational structure of molecules, the Fano effect, resonance effects in autoionization, and Cooper minima can be explored through molecular photoelectron spectroscopy. Soft x-ray photoelectron spectroscopy with synchrotron radiation can lead to important information on partial photoionization cross sections, relaxation effects, and atomic multiplet structure. The angular distribution of photoelectrons can be studied to advantage, and experiments in excited-state photoelectron spectroscopy become accessible.

National needs in synchrotron radiation research should be examined. Both the level of support for on-going research and plans for future facilities deserve thorough consideration, in view of growing interest in the subject and rapid development abroad. Although plans in this area are not within the direct purview of the panel, we wish to call attention to the importance of immediate and far-reaching efforts in this expanding field.

APPENDIX C
QUESTIONNAIRE

July 8, 1974

Dear Colleague:

The NAS/NRC Committee on Atomic and Molecular Physics, at its meeting on April 23 of this year, decided that it would take an active role in certain aspects of the connection between accelerators and atomic physics research. The chairman of the Committee, Felix T. Smith, consequently appointed an *ad hoc* Working Panel on Accelerator-Related Atomic Physics Research, consisting at this stage of the undersigned.

Our Panel has been charged with the task of studying atomic physics research possibilities on large and unique national facilities as well as on local facilities at various universities and institutions, and to formulate recommendations for action by the Committee on Atomic and Molecular Physics. Furthermore, we are to initiate communication with atomic physicists and with other physicists connected with the pertinent facilities, in order to convey information on research possibilities to atomic physicists, and to provide input from atomic physicists into the planning and design of new facilities.

It seems to us desirable to determine what facilities are in fact now used or scheduled for use in atomic physics research. Therefore, we are beginning our work by making a census of current activity in the field. We would much appreciate your response to the enclosed brief questionnaire, returning it at your earliest convenience and no later than September 1, 1974.

A list showing the distribution of this letter is enclosed. This mailing is being sent to a large number of individuals in various laboratories, and in many cases to more than one person in a particular accelerator laboratory. One response per laboratory is sufficient; if several overlapping questionnaires are returned, we shall combine them and eliminate redundancies. If you are aware of any additional accelerator laboratories with which we should get in touch, please let us know; it is important that this survey be as exhaustive as possible.

We would also be grateful for any comments or suggestions that you may have with regard to our Panel's task. Some of you have already written to Felix Smith on this subject, in response to his letter of February 28, 1974. We have copies of those replies; additional remarks are, of course, most welcome. We would be especially grateful for suggestions recommending additional members for our Working Panel.

The information which we collect will be made available to all participants.

Thank you for your cooperation.

Sincerely yours,

/signed/

Bernd Crasemann, Chairman
Eugen Merzbacher

P.S. Please mail your responses to B. Crasemann, Dept. of Physics, University of Oregon, Eugene, Oregon 97403.

July, 1974

Ad Hoc Working Panel on Accelerator-Related Atomic Physics Research

Survey Form

1. Laboratory or Institution:
2. Research in atomic physics, connected with accelerators in this laboratory,
   ( ) is currently being conducted
   ( ) is planned for the near future
3. Brief description of accelerators used (or to be used) for atomic physics research:
4. Names of investigators in charge of atomic physics research programs at these accelerators:
5. Total number of scientific personnel involved in this research:
   How many of these are graduate students?
6. Approximate fraction of available beam time devoted to research in atomic physics:
7. (Optional) Please list the sources of funding support for accelerator-related atomic research at your institution:
8. Brief description of major topics of investigation:
9. Respondent's name, title, address:

Please return to: B. Crasemann
Physics Department
University of Oregon
Eugene, Oregon 97403

APPENDIX D
U.S. LABORATORIES CURRENTLY CONDUCTING RESEARCH IN ATOMIC PHYSICS WITH ≥100-KEV ION ACCELERATORS

Argonne National Laboratory (FN VdG; 4.5-MV Dyn; 2-MV VdG)
Arizona, University of (5.5-MV VdG; 2-MV VdG)
Battelle Pacific Northwest Laboratory (2-MV VdG)
Bell Laboratories (2-MV VdG; 2 300-keV heavy-ion accelerators; users)
Brigham Young University (2-MV VdG)
Brookhaven National Laboratory (MP-6 MP-7 VdG; 3.5-MV VdG)
California Institute of Technology (1.8-MV VdG)
California, University of, Davis (see Crocker Nuclear Laboratory)
Center for Astrophysics, HCO/SAO (users at Brookhaven National Laboratory)
Chicago, University of (users at Argonne National Laboratory)
Connecticut, University of (200-kV CW; 1-MV VdG; also users at ORNL)
Cornell University (2.5-MV Dyn)
Crocker Nuclear Laboratory (76-in. isochronous cyc)
Duke University (see Triangle Universities Nuclear Laboratory)
East Carolina University (4-MV VdG)
Florida State University (FN VdG)
Georgia Institute of Technology (1-MV VdG)
IBM T. J. Watson Research Center (3-MV VdG; 400-kV VdG)
Idaho State University (2-MV VdG)
Joint Institute for Laboratory Astrophysics (users at ORNL)
Kansas, University of (3.5-MV VdG)
Kansas State University (EN VdG; 3-MV VdG; 100-kV CW)
Kentucky, University of (5.5-MV VdG)

This list was compiled from responses to the panel's survey questionnaire. Accelerator types are abbreviated as follows: CW, Cockcroft-Walton; cyc, cyclotron; Dyn, Dynamitron; VdG, Van de Graaff.

Lake Forest College (users at ORNL)
Lawrence Berkeley Laboratory (Super-HILAC)
Lockheed Palo Alto Research Laboratory (3-MV VdG)
Los Alamos Scientific Laboratory (3.75-MV VdG)
Maryland, University of (3-MV VdG)
Minnesota, University of (MP VdG)
Montana State University (150-kV CW)
Naval Research Laboratory (5-MV VdG; 300-kV VdG)
Nebraska, University of (400-kV RF source; 150-kV RF source)
New York, State University of, Albany (4-MV Dyn; users elsewhere)
New York, State University of, Stony Brook (FN VdG)
New York University (300-kV CW)
North Carolina State University (see Triangle Universities Nuclear Laboratory)
North Carolina, University of (see Triangle Universities Nuclear Laboratory)
North Texas State University (2.5-MV VdG)
Oak Ridge National Laboratory (isochronous cyc; EN VdG; 5.5-MV VdG; 3-MV VdG; 2.5-MV VdG; 200-kV accelerator; 100-kV heavy ion source)
Ohio State University (CN VdG)
Rochester, University of (MP VdG)
Rutgers University (FN VdG; 2-MV VdG)
Sandia Laboratories (2.5-MV VdG; 1-MV VdG; 100-kV accelerator)
Stanford University (FN VdG)
Tennessee, University of (users at ORNL)
Texas A and M University (88-in. variable-energy cyc)
Texas, University of, Austin (EN VdG; 5-MV VdG; 4-MV VdG; 2-MV VdG)
Texas Christian University (150-kV CW)
Toledo, University of (400-kV VdG)
Triangle Universities Nuclear Laboratory (15-MeV cyc injecting into FN VdG; 4-MV VdG)
Virginia, University of (5.5-MV VdG; 1-MV VdG)
Virginia Polytechnic Institute and State University (users at Brookhaven National Laboratory)
Washington, University of (FN VdG)

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