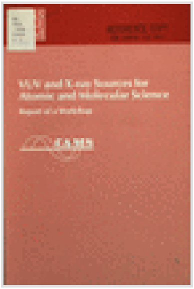

VUV and X-Ray Sources for Atomic and Molecular Science: Report of a Workshop (1986)

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Report of a Workshop

CAMS

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Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics,
and Resources
National Research Council

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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.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

The National Research Council's Committee on Atomic and Molecular Sciences (CAMS) convened a workshop on November 8-9, 1984, to review the current status of short-wavelength light sources of interest to the atomic, molecular, and optical (AMO) physics community. The general intent of the Committee was to (1) review advantages and disadvantages of existing technologies in the ultraviolet (UV) and x-ray spectral range, and (2) determine which of these technologies, if any, is best suited for particular problems in AMO physics. Proponents of the major sources of radiation in the UV and x-ray spectral range participated in the workshop. The general consensus of the participants was that the differentiation between the available technologies is based largely on the requirements of the applications, and that each of the currently available technologies has its benefits and drawbacks. Improved optics and design are needed for all technologies discussed in these workshop proceedings.

Lloyd Armstrong, Jr., Chairman
Workshop on VUV and X-Ray Sources
for Atomic and Molecular Science

I

Workshop Overview

SHORT WAVELENGTH RADIATION FACILITIES FOR ATOMIC, MOLECULAR, AND OPTICAL PHYSICS

Many of the exciting new frontiers in atomic, molecular, and optical (AMO) science lie at energies greater than 5 eV, energies that correspond to the VUV, XUV, and soft x-ray portions of the electromagnetic spectrum. In this energy range, complex interactions involving many particles dominate the physics of energy transfer in excited states of atoms and molecules. Fundamental questions concerning the nature of these multiparticle interactions, as well as their temporal evolutions, are at the core of many of the most important new investigations in AMO physics. While investigations of atomic and molecular systems in the UV, XUV, or soft x-ray energy regime offer unique opportunities to examine these interactions in a systematic way, advances have been hindered because of the difficulty in developing the necessary sources of radiation. The purpose of this workshop on facilities was to review the current status of sources of radiation greater than 5 eV, and it brought together people concerned with the development and use of sources in this regime.

Participants in this workshop included prominent spokesmen for the three major sources of radiation in the UV and x-ray spectral range: synchrotron radiation from storage rings, coherent radiation (either from direct (laser) XUV generation or frequency multiplication from visible lasers), and XUV radiation from laser- induced plasmas. Only a few years ago such a gathering of strong proponents of these diverse technologies would have generated considerable argument over which facility type is the best, or which should be developed most rapidly. However, from the discussions among the participants at this workshop, it is clear that the field of XUV generation has matured to the point that there is wide agreement as to what are the capabilities and limitations of the various techniques. This understanding has led to differentiations between the technologies based largely upon the requirements of the application, rather than on some preconceived notion of absolute merit.

The general characteristics of the three major types of sources are:

1. SYNCHROTRON RADIATION is collimated light which is extremely broad band, with relatively high average power. Synchrotron light sources, next to lasers, are the brightest sources of light known to man, and depending upon the energy of the stored electron beam and the strength of the magnetic fields in the bending magnets or wigglers, this radiation can extend from the infrared to well into the hard x-ray wavelengths. The radiation is produced as bursts with durations on the order of 100-500 psec, at a repetition rate of 1-100 MHz. For spectroscopy, the radiation must be monochromatized. Recent advances in the design of insertion devices (wigglers and undulators) cause the spectrum to be bunched in regions of interest, enhancing peak spectral brightness and introducing a degree of coherence. Synchrotron radiation facilities are, by their nature, large and expensive, and those who wish to use synchrotron radiation must travel to national facilities.

2. COHERENT XUV is extremely high peak spectral brightness sources, with diffraction limited divergence. These sources can produce pulses of extremely short duration, but for large peak powers, the repetition rates are low, as is the average power. For spectroscopy, the coherent light sources generated by frequency multiplication from the visible have potentially very high resolution, exceeding even the

largest spectrometers in the XUV. These sources, while in principle currently available for any wavelength down to 355 Å and small enough to exist in the average laboratory, are at present difficult to operate, and a given configuration can only be used to generate a relatively narrow band of wavelengths. Thus spectroscopies that require broad sweeps of wavelengths are impractical with current XUV coherent sources. (Many of these limitations would be neatly overcome if new designs for free electron lasers operating in the XUV were shown to be practical).

3. **LASER GENERATED PLASMA** is uncollimated, broad-band light with high peak flux. Depending upon the target material and the intensity of the laser pulse, these sources can produce light from the visible down to wavelengths as short as 10 Å. The pulse duration of the radiation depends upon the pulse duration of the laser used, as well as the target material and the wavelength of the output radiation. These sources are relatively compact and can be set up in a small laboratory. The output radiation must be monochromatized for spectroscopy. For high repetition rate applications, the engineering problem of isolating delicate optics and other components from the resulting debris of the plasma must be solved.

The output of these light sources can be described by a variety of terms including intensity, flux, and spectral intensity. When evaluating sources for their appropriateness to different types of experiments it is essential that one choose the particular characterization of sources that is best suited to the specific situation. It rapidly becomes clear that there is no single best source that is appropriate for all experiments. In order to provide a guide to some of the contrasting strengths and weaknesses of various sources, Table 1 provides a comparison of several sources under six different characterizations.

The specific spectral intensity (sometimes called brightness) is the number of photons per unit time crossing a unit area in a unit solid angle and a unit spectral bandwidth. In the absence of elements that absorb or amplify, the specific spectral intensity is a conserved quantity and it is related to the degree of excitation of fundamental modes of the radiation field.

In many cases it is desirable to have a large number of photons crossing a large area with only a secondary concern about the angle of incidence. In these cases more interest is associated with the spectral flux or photons per unit time per unit bandwidth. The spectral flux is a measure of the total power emitted over all solid angles from the entire source area in a given bandwidth.

In both the above parameterizations the output per unit bandwidth is used. In many cases the bandwidth usable in an experiment is relatively large and often it is best described as a fraction of the incident frequency. For this reason in the parameterization of brilliance or photons per unit time crossing a unit area in a unit solid angle and a bandwidth of 0.1 percent, the incident frequency has been introduced.

Clearly a monochromatic source such as a laser can have a very specific spectral intensity with a comparatively lower brilliance and an even lower flux relative to a nonmonochromatic source. Finally, all sources below 100 nm are pulsed and can be described in terms of their peak values and their average values.

All of these sources of XUV are only as useful as the supporting technology for focusing and collecting the light. One of the major efforts in the field is the development of XUV optics using the microfabrication techniques of the semiconductor industry. For example, mirrors for the reflection of XUV light at nearly normal incidence are made by laying down on a substrate precisely controlled thicknesses of alternating layers of high and low Z material in order to make a "synthetic" crystal for Bragg reflection. Another example is the fabrication of zone plates in order to focus XUV light, with the possibility of producing x-ray microscopes with unprecedented resolving power. Several speakers at this workshop will emphasize the need for a larger effort in this field, noting that none of the XUV sources is of any real use in experiments without high efficiency optics.

In the material that follows, six topics of special interest to the AMO community are discussed in order to illustrate how the type of experiment to be done dictates the choice of type of photon source. In each instance, the importance of the physics that is to be done makes a strong case for further development of the corresponding photon source.

EXAMPLE: Time-Resolved Energy Transfer on Surfaces of Solids
Radiation Requirement: Ultra-short pulses of high intensity XUV
Facility Choice: Short-pulse XUV laser

Over the last five years, there has been a renewed interest in all aspects of the surfaces of solids; e.g., geometry of the bulk lattice at the surface, electronic states of these surface atoms, positions of adsorbate atoms on surfaces, and perturbations of these atoms by the underlying bulk. This subject is also an interface between condensed-matter and AMO physics, and the AMO community is beginning to play a significant role in the new directions in which this field is developing.

Virtually all of the investigations of surfaces to date have been made using steady-state techniques, resulting in information about surfaces that is largely restricted to equilibrium, ground-state configurations. Thanks to the impact of picosecond pulse lasers, this restriction is now being lifted with the development of time-resolved photoemission techniques. Time-resolved photoemission involves a short pulse of visible, or near-infrared, light to "pump" the surface atoms into an excited state. At some subsequent (short) time later, a pulse of UV or XUV light is used to "probe" the excited state population. The resulting electrons that are photoemitted are recorded using a time-of-flight electron energy analyzer. The measurement consists of recording the complete electron energy spectrum as a function of various time delays between the pump and probe light pulses. This information is readily unfolded to reveal the energy spectrum of otherwise unpopulated excited states, as well as the temporal evolution of the population. Just as in normal photoemission, information about the energy-momentum dispersion is obtained by resolving the electrons according to their angle of emission as well as to their energy. An experiment that demonstrates the potential of this technique has been recently reported on the (110) surface of cleaved InP. This experiment, using 50 psec pulses of light at 5320 Å for the pump and at 1182 Å for the probe, demonstrated the enormous scientific potential of performing time-resolved studies on surfaces. The next generation of experiments of this type will require pulses of light of duration less than 1/2 psec for the pump and probe in order to time-resolve the decay of excitation, and thus reveal the mechanisms of energy transfer. Further, tunable, short-pulse light in the XUV for the probe would greatly increase the types of solids and surfaces that could be investigated. All of these changes will require significant advances in coherent XUV and UV short pulse light generation.

EXAMPLE: Dynamics of Deep Inner-Shell Processes
Radiation Requirement: Broadly tunable, high energy
Facility Choice: Synchrotron radiation from a high energy storage ring

Deep atomic hole states have peculiar properties: the energies are high (the 1s binding energy reaches 100 keV at atomic number Z=87), transitions are mostly radiationless and very fast, straining the limits of perturbation theory; there are many decay channels, leading to very short hole-state lifetimes, with concomitant widths as large as tens of electron volts. Relativistic and quantum electrodynamic effects are pronounced and sometimes dominate over classical phenomena. We illustrate the scientific potential of the field with three examples of inner-shell processes that promise to lead to new insights: threshold excitation phenomena, many-body effects on energy levels, and relativistic and QED effects on deep hole states.

The excitation of atoms and their de-excitation through emission of photons or Auger electrons is usually considered to occur in two steps, separated by intervening relaxation of the electron cortege. This two-step model breaks down near thresholds of inner-shell excitation. The breakdown is epitomized by the resonant Raman effect, which occurs when an inner electron is promoted to an excited state by a photon of exactly the right energy (within the lifetime width); the state decays resonantly through an x-ray or Auger transition, in a single quantum step. Above resonance, the single-step mechanism blends into the two-step mechanism via post-collision interaction, through which energy is fed from the receding photoelectron to the emitted Auger electron. These phenomena can potentially lead to exceedingly precise spectroscopic measurements, and to novel ways for sensing the decaying atom's solid state environment.

Atomic phenomena provide a particularly fertile testing ground for new approaches to the understanding of many-body phenomena, because the atomic potential is rather well-known and the independent particle model generally is a good first approximation. There is a pronounced, as yet incompletely explored correlation shift of inner-shell energy levels, because of interactions between bound-state configurations as well as to "Coster-Kronig fluctuations" to virtual excited states--the radiationless analog of the electron self energy. Only many-body wave functions will permit a quantitative description of this phenomenon. Experiments with broadly tunable x-ray radiation from storage rings can provide important guideposts for the difficult theoretical efforts in this field.

The strength of relativistic and quantum electrodynamic effects on deep hole states in heavy atoms is surprising. The Breit interaction (the first correction to Coulomb's law, to lowest order in the fine-structure constant) reduces the 1s binding energy in uranium by 480 eV; the self energy and vacuum polarization, which together produce the Lamb shift, amount to 344 and 86 eV, respectively, for this state. In some phenomena, the static Coulomb interaction nearly cancels, leaving a dominant role for the dynamic corrections expressed by the Breit term; examples are fine-structure splitting and x-ray hypersatellite shifts. The next generation of synchrotron radiation sources can be expected to give experimental access to these phenomena, leading to delicate tests of theory.

EXAMPLE: The Three-Body Continuum Problem
Radiation Requirement: Broadly tunable, high energy, narrow bandwidth
Facility Choice: Synchrotron radiation from a low to medium energy storage ring; radiation from laser-induced plasmas

The three-body continuum Coulomb problem is not merely one of the oldest unsolved problems in atomic and molecular physics, but one of the oldest in all of physics. It is particularly important, of course, in atomic and molecular physics where Coulomb forces are overwhelmingly dominant. Basically, the difficulty results from our inability to characterize the asymptotic form (or boundary conditions) for a wave function describing three (or more) unbound charged particles such as those that result from the double photoionization of He:

$$h\nu + He \rightarrow He^{++} + e^- + e^-$$

or the double photodetachment of H^-

$$h\nu + H^- \rightarrow H^+ + e^- + e^-$$

Since the equation describing the wave function is a partial differential equation (Schroedinger or Dirac Equation), we cannot begin to solve it without boundary conditions, even though the forces are very well known.

Atomic and molecular physics provides an outstanding laboratory to gain insight into this problem precisely because the forces are known so well; the only unknown is the boundary condition of the wave function. Careful measurements, then, on energy distribution and angular correlations in various situations could result in fundamental information on the problem. Among the specific experiments in this area are the following:

1. double photoionization of atoms and molecules;
2. inner shell photoionization in coincidence with an Auger electron; and
3. double Auger decay.

These experiments require a photon source that is intense, has high resolution, and is tunable over a broad energy range.

EXAMPLE: Molecular Photophysics
Radiation Requirement: Broadly tunable; narrow bandwidth with high peak power
Facility Choice: Low to medium energy storage ring; UV and XUV laser sources

One major focus of molecular photophysics has been the study of intense quasibound resonances in the ionization continuum, e.g., shape and autoionizing resonances. Such resonances temporarily freeze the excited molecular complex in a quasibound state, thus amplifying the more subtle dynamics of the photoionization process. Synchrotron radiation has been pivotal in elucidating the properties of molecular shape resonances. This work has had a major impact on the study of absorbed molecules in which shape resonance characteristics are substantially preserved. Several new opportunities exist in this general vein but require enhanced light source capability. The study of shape-resonance-induced vibrational effects in polyatomics will produce insight into interactions involving complex vibrational motion. This subject remains essentially unexplored and would require higher sensitivity and electron energy resolution than used to date. Another important extension is to shape resonances populated from deep inner shells. These are fundamentally important because complications in valence shell excitations are turned off and because Auger decay and other relaxation processes provide additional information.

A very timely advance would involve studying the photoelectron branching ratios and angular distributions as a function of position within autoionizing resonances. Extensive work on total adsorption profiles has had major impact on atomic and molecular physics; however, knowledge of the decay channels (vibrational and electronic branching ratios) would greatly advance our understanding of the dynamics of this ubiquitous mechanism. Partially resolved, prototype measurements on the broadest known resonances have been made--indication that significant improvements in the photon bandwidth of synchrotron radiation facilities are required for major progress.

When an inner-shell hole is produced in a molecule, an energy greatly in excess of the molecule's binding energy is stored in the molecule, resulting in a violent breakup of the molecule. This decay results from multiple Auger transitions, leading to a highly charged molecular core that flies apart via Coulomb repulsion. This "Coulomb explosion" mechanism was discovered long ago with x-ray tubes. It is now possible, using advanced synchrotron radiation sources, to produce inner-shell holes on different locations in a molecule, and even to "park" the excited electron in localized resonances during explosive decay. Detailed studies of the mechanisms involved in fragmentation of inner-shell molecular hole states under selective conditions are ripe for study.

Advanced tunable laser sources in the UV and XUV offer a different form of selectivity in molecular excitation. Use of the narrow bandwidth and high peak power permits the probing of molecules in ways unimaginable before modern lasers. In particular, it is becoming increasingly possible to prepare single excited quantum states of molecules and to probe the dynamics of their further excitation and/or decay. Hence, we are able to examine excited states at the quantum state specific level in much the same way that we have always studied ground states. Prototype studies have been carried out in which resonant multiphoton ionization with photoelectron detection has been rotationally resolved at each stage of the multistep process. As laser sources advance, such detailed excitation schemes can be greatly extended in both spectral range and target variety.

These advanced excitation/interrogation schemes open up many new opportunities in molecular physics. For example, photoelectron branching ratios and angular distributions resulting from photoionization of single excited quantum states will provide fresh, new challenges to a field heretofore limited to photoionization of ground states. The study of alignment of excited states and ions and of fragmentation of excited quantum states is advancing rapidly. Multiphoton excitation through single quantum states greatly simplifies the spectroscopy of higher lying states and permits the study of nonoptical manifolds. Significantly, this includes nonoptical autoionizing states, which have not been observed by other means.

EXAMPLE: Production of Slow Cold Ion Beams
Radiation Requirement: High intensity x rays
Facility Choice: Medium to high energy storage ring, UV laser

The generation, confinement, and manipulation of ions in a wide variety of states of ionization and excitation have great utility in a manifold of diverse applications. Examples are the production of fusion plasmas, characterization of a wide range of astrophysical environments, development of new frequency standards, and the design of accelerators and storage rings. In many of these applications it is desirable to produce slow, cold ions. Especially for high states of ionization and excitation, the ability to do so has been severely constrained. For example, plasmas hot enough to generate such ions typically have temperatures of tens to hundreds of keV, and typically produce them in dirty, high density environments. Colder but still fast unidirectional beams of ions are available from collisional ionization and excitation of charged particle beams.

In recent years, substantial headway has been made in the creation and storage of singly- and multiply-charged recoil ions produced at eV energies by high velocity, highly charged fast projectile beams in dilute gas targets. These slow recoil ions have themselves been utilized to form secondary beams for ion-atom and ion-molecule collision experiments. However, temperatures of a few eV still correspond to tens of thousands of degrees Kelvin. Developing efficient ways to make multiply ionized, excited ions at room temperature would amplify opportunities for collision and spectroscopy experiments enormously. Consider what the impact would be, for example, on studies of chemical reaction dynamics if beams in the range of 1 to 10 eV per charge with energy spread < 10 percent were available. Applications to characterizing processes of possible importance in x-ray laser development alone would justify the effort in developing such beams. Cooling to still lower temperatures, which would multiply applications, is also likely to be easier at starting temperatures of 300 K as opposed to tens of thousands of degrees Kelvin.

The recent advance of high brightness photon beams from synchrotron storage rings and UV lasers has made possible the consideration of energetic photons as a direct ionizing agent for the first time. It now appears to be possible to create significant numbers of multicharged ions by successive photoionization within reasonable times. For example, white light from wigglers attached to the most advanced x-ray rings of the present day is calculated to be able to ionize completely argon ions to the bare nuclear state within a few seconds, provided the ions are trapped in the light beam for this time. X rays harder than the K edge of the target species are also capable of direct production of multicharged ions in single, low momentum transfer photoionization events, since rapid Auger cascades subsequent to the primary ionization event spontaneously occurring.

Extraction of cold, high charge state ions from the photoionization region provides a unique source. Depending on wiggler photon brightness, source region dimensions, and timing characteristics of the ring, it appears feasible to extract 10^4 to 10^8 ions per second from a source region of millimeter dimensions at unprecedentedly low temperatures. Such a high brightness source has a potentially broad range of exciting applications, extending from atomic beam chemistry to injection of heavy ion storage rings equipped with efficient electron-ion cooling devices.

EXAMPLE: Coherent Excitation in Extreme Field Conditions
Radiation Requirement: Extremely high peak power coherent light
Facility Choice: Short-pulse UV laser with amplifier

One of the central problems in atomic physics is the investigation of atoms and molecules under extreme conditions. An example is the behavior of matter when it is subjected to extremely high electric fields, fields on the order of an atomic unit (1 a.u.= $e/a_0^2 = 5 \times 10^9$V).

Recent research findings lead to the conclusion that the direct multiphoton excitation of appropriate amplifying media with high brightness ultraviolet sources is a very promising choice for the generation of short wavelength radiation in the kilovolt range. The class of physical mechanisms that dominate the physics of matter at this field intensity appears to involve collective electronic motions, and it has been recently shown to exhibit surprising characteristics which suggest which entirely new approaches for the efficient production of x rays are feasible.

From an analysis of certain data obtained to date, which includes information on the atomic number (Z), intensity, frequency, and polarization dependencies, the following approximate description of the electronic motions involved in these processes has emerged. The data strongly indicate that a collective response of an entire shell, or a major fraction thereof, is directly involved in the nonlinear coupling. Collective responses of atomic shells have been discussed previously in relation to the mechanism of single photon photoionization. These studies simply point to a nonlinear analog of this basic electronic mechanism. With this picture, the outer atomic subshells are envisaged as being driven in coherent oscillation by the intense ultraviolet wave. (An oscillating atomic shell, quantum mechanically, would be represented by a multiply excited configuration.) Atomic motion of this type is not at all unexpected. It is known, for example, for the case of xenon, particularly from photoionization studies involving multiple electron ejection, the 5p,5s, and 4d shells exhibit substantial intershell coupling and behave in a collective fashion in a manner resembling a single supershell. An immediate consequence of this type of behavior is an increase in multiphoton coupling resulting directly from the larger magnitude of the effective charge involved in the interaction. In this way, a multielectron atom undergoing a nonlinear interaction responds in a fundamentally different fashion from that of a single electron atom. Interestingly, the motion envisaged has a nuclear counterpart known as the giant dipole, a phenomenon that can also be manifested in higher multipoles.

Modern rare gas halogen laser systems, scaled up to large diameter and employing femtosecond pulse width technology, should allow basic physical studies to be performed in an intensity range exceeding 10^{20} W/cm^2. In terms of energy density, this is on the scale of that produced by thermonuclear environments. At such an intensity, the peak electric field of the coherent driving wave approaches the unprecedented value of 50 a.u. In such an extreme environment, which is impossible to generate by any other known physical means, it is likely that physical processes never previously observed will be detected. This would include certain mechanisms involving the production of electron-positron pairs.

It should be noted that at energy densities of the scale stated above, an atom experiences a violent perturbation that has important features in common with certain well-studied collisional phenomena such as ion-atom collisions, electron-ion collisions, and beam-foil interactions. Indeed, in the case of beam-foil collisions, a radiative environment at an intensity of 3 x 10^{18} W/cm^2 at an ultraviolet wavelength approximates, in several important respects, the conditions associated with the passage of an argon ion through a carbon foil with a kinetic energy of ~ 1 GeV. This rough similarity leads to the consideration of the concept of an "optical solid" in which stationary atoms in a sufficiently intense radiative field will experience an interaction comparable to that of energetic ions traversing solid matter.

Table 1. Comparison of Characteristic Outputs for Various XUV and Soft X-Ray Sources

	Photon Energy	Beam Divergence	Pulse Duration	Beam Area	Repetition Rate	Specific Spectral Intensity (Brightness)		Spectral Flux		Brilliance	
		rad	sec	mm^2		Phot. sec^{-1} mm^{-2} MHz^{-1} sr^{-2}		Phot. sec^{-1} MHz^{-1}		Phot. sec^{-1} mm^{-2} sr^{-1} (0.1% BW)$^{-1}$	
	eV	$\Delta\phi$, $\Delta\theta$			Hz	Peak	Avr	Peak	Avr	Peak	Avr
Current Synchrotron Radiation Sources											
Bending Magnets	$\leq 10^3$	10^{-3}; 5×10^{-3}	10^{-9}–10^{-10}	0.2	10^6–10^7	5×10^7	5×10^4	5×10^5	5×10^5	5×10^{17}	5×10^{14}
Wigglers	$\leq 10^3$	10^{-3}; 5×10^{-3}	10^{-9}–10^{-10}	3	10^6–10^7	5×10^7	5×10^4	5×10^8	5×10^6	10^{16}–10^{18}	10^{13}–10^{15}
Advanced Light Source (Proposed)											
Wigglers	$\leq 2\times10^4$	10^{-3}; 10^{-4}	2×10^{-11}	.03	5×10^8	5×10^{10}	5×10^8	10^9	10^7	10^{18}	10^{16}
Undulators	$\leq 2\times10^3$	4×10^{-3}; 10^{-4}	2×10^{-11}	.03	5×10^8	10^{16}	10^{14}	10^{13}	10^{10}	10^{20}	10^{16}
Laser Sources											
Direct generation	≤ 5	Diffraction Limit	$\geq 10^{-13}$	Diff. Lim.	C.W.	10^{23}	10^{17}	10^{21}	10^{13}	10^{27}	10^{20}
Upconversion	≤ 20	Diffraction Limit	$\geq 10^{-13}$	Diff. Lim.	$\leq 10^3$	10^{20}	10^{14}	10^{18}	10^{12}	10^{20}	10^{15}
Noncoherent Sources											
Laser Generated Plasmas	$<10^3$	$\pi/2$, 2π	$\geq 10^{-11}$	.01	10^3	10^{11}	10^4	10^{13}	10^7	10^{18}	10^{11}
Flash X-Ray	$<10^3$	$\pi/2$, 2π	5×10^{-8}	10	1	10^3	10^{-4}	10^{11}	10^4	10^{13}	10^6
Rare Gas Continua	<25	2×10^{-2}; 2×10^{-2}	5×10^{-7}	5	10^4	10^7	5×10^4	4×10^8	2×10^7	10^{13}	10^8

II

Workshop Papers

1. ATOMIC AND MOLECULAR PHYSICS WITH VUV AND X-RAY PHOTONS

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I. WHY PHOTON IMPACT?

Studies of atomic and molecular properties using incident photons have two important advantages compared to studies using incident particles: the interaction of photons with a target is small and well understood, and the photon disappears after the photoabsorption process, leaving only the target (see Figure 1.1). As a result, by using photons as the probe, one can concentrate on the properties of the target rather than on the interaction process.

In important energy ranges, incident photons provide better energy resolution than any other incident particle (Figure 1.2). Furthermore, photoabsorption limits the number of final states to only those which are optically allowed, leading to clean, easily interpretable experiments. The results are often invaluable in the interpretation of very much more complicated electron and ion impact experiments.

For certain types of precise experiments it is essential to know the orientation of the spin, i.e., the polarization of the incident particle. Photons are easily polarized; electrons and ions are not!

It is thus clear that photon impact spectroscopy is excellent for the study of atomic and molecular physics for a variety of reasons. The following informal outline summarizes a number of problems and the relevant experiments. In the parentheses to the left of each experiment, the spectral region required (U for UV and X for x ray) is specified.

II. WHAT CAN BE STUDIED USING PHOTONS?

A. Three-Body Continuum Coulomb Problem

The three-body continuum Coulomb problem is one of the oldest unsolved problems in physics. The difficulty arises from our inability to characterize the boundary conditions for a wave function describing three (or more) unbound charged particles; boundary conditions are crucial to the solution of partial differential equations such as the Schrodinger equation. Among the experiments that bear on this problem are the following:

(U,X) 1. double photoionization/photo detachment (see Figures 1.3 and 1.4);
(U,X) 2. inner shell photoionization in coincidence with an Auger electron (see Figure 1.5); and
(U,X) 3. double Auger decay (see Figure 1.6).

B. Strong Correlation/Multiple Processes

These studies focus on the correlated motion of two (or more) electrons. A typical manifestation of this correlation is a multiple process which would be impossible in a one-electron picture. Some experiments are:

(U,X) 1. ionization plus excitation by a single photon (satellite lines) (see Figures 1.7 and 1.8);
(U,X) 2. autoionizing state studies (see Figure 1.9); and
(U,X) 3. investigations of the large perturbations of interchannel coupling by studies of subshells with small partial cross sections (see Figure 1.10).

C. Photoabsorption by Unusual States

These investigations extend our understanding of fundamental atomic and molecular interactions to new vistas. Among the interesting targets to study are the following:

(U) 1. Excited states of atoms and molecules. These studies would give information on the interaction process which takes place over a broad spatial range and not just over a few Bohr radii as for ground states (see Figures 1.11 and 1.12).

(U,X) 2. Open-shell atoms. Although these constitute a majority of the periodic table, there is virtually no extant data. These offer the possibility of studying non-central interactions, which are not observable in spherical, closed shell atoms.

(U,X) 3. Ions are important in many scientific and technological scenarios, but there is almost no experimental data. In addition, the possibility exists of studying simple (few-electron) high-Z systems.

D. Probes of Small Interactions

This class of investigations probes forces that are often masked by larger effects but can be "unmasked" with clean, well-resolved photons. This category includes the following:

(U,X) 1. Photoionization of high-Z atoms-studies focusing on relativistic efforts (see Figure 1.13);

(X) 2. Partial cross sections of inner atomic shells near threshold, probing the atomic EXAFS predicted by theory to understand how this might affect molecular, surface, or solid EXAFS (see Figure 1.14);

(U,X) 3. Photoelectron angular distribution and spin polarization measurements, studies that are sensitive to matrix elements (not just absolute squares) and their phases (see Figure 1.15); and

(U,X) 4. "Complete" experiments measuring total cross section, partial cross sections, photoelectron angular distributions, and spin polarization, allowing deduction of all matrix elements and phases.

E. Other

(U,X) 1. Atomic/molecular cluster photoionization to determine how many are needed to constitute a surface or a solid.

2. Atomic/molecular/solid photoionization comparative studies to isolate molecular and solid state effects (see Figure 1.16).

(U,X) 3. Use of photoionization to create ions to be stored and employed as targets in other experiments such as ionic photoionization, ion-ion and electron-ion collisions.

III. FINAL REMARKS

Great opportunities await us in the investigation of atoms and molecules with photons. Significant contributions to both fundamental understanding and applications are to be made. It would be sad, indeed, to let these opportunities pass us by.

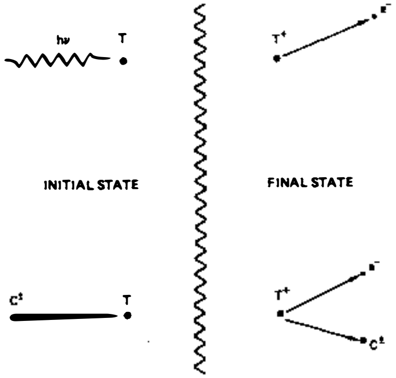


FIGURE 1.1. Comparison of the ionization processes induced by photon and charged particle impact.

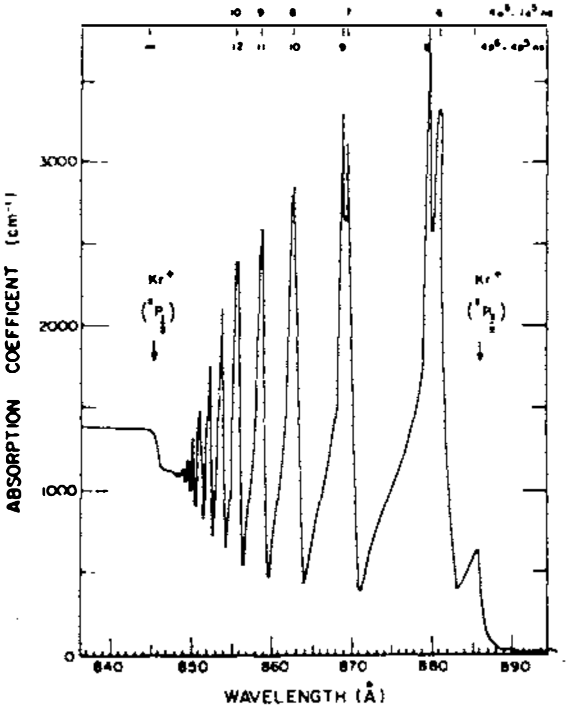


FIGURE 1.2. Photoabsorption cross section of Krypton near threshold.

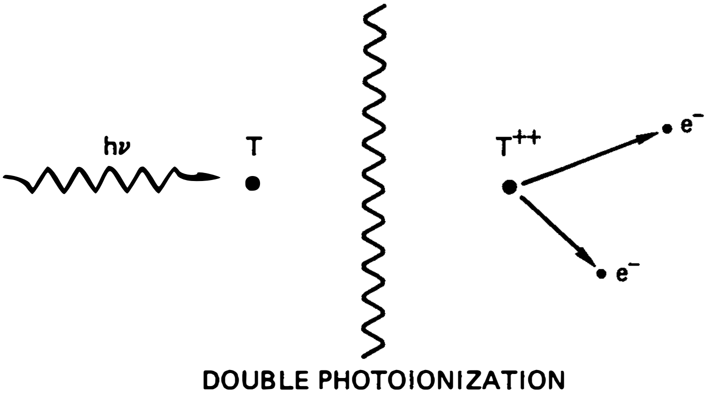


FIGURE 1.3. The double photoionization process.

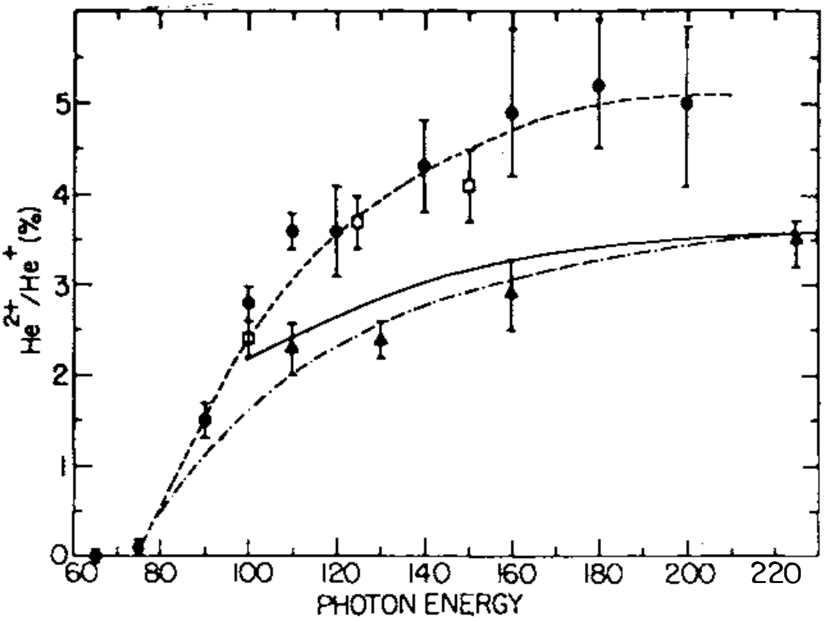
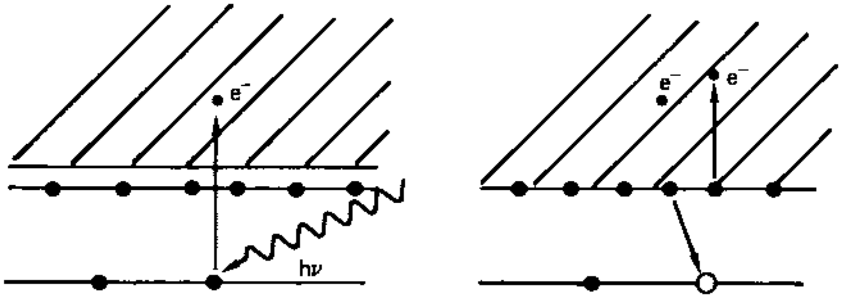
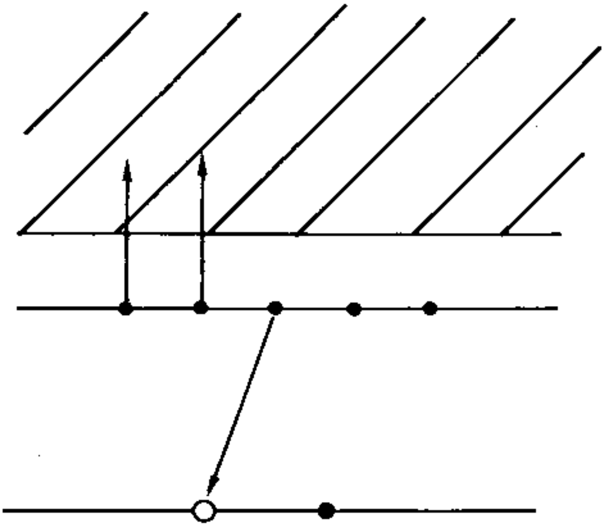


FIGURE 1.4. Ratio of double to single photoionization of helium. The points are experimental and the curves are experimental. Note the discrepancies.



INNER SHELL THRESHOLD IONIZATION–
AUGER CORRELATION
(POST-COLLISION INTERACTION)

FIGURE 1.5. The inner shell photoionization followed by Auger decay process.



DOUBLE AUGER DECAY

FIGURE 1.6. The double Auger decay process.

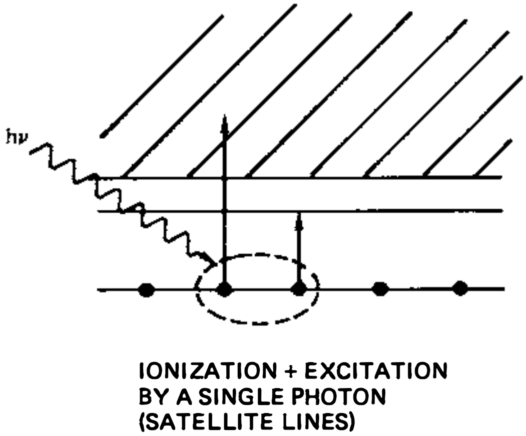


FIGURE 1.7. The process of ionization *plus* excitation by a single photon.

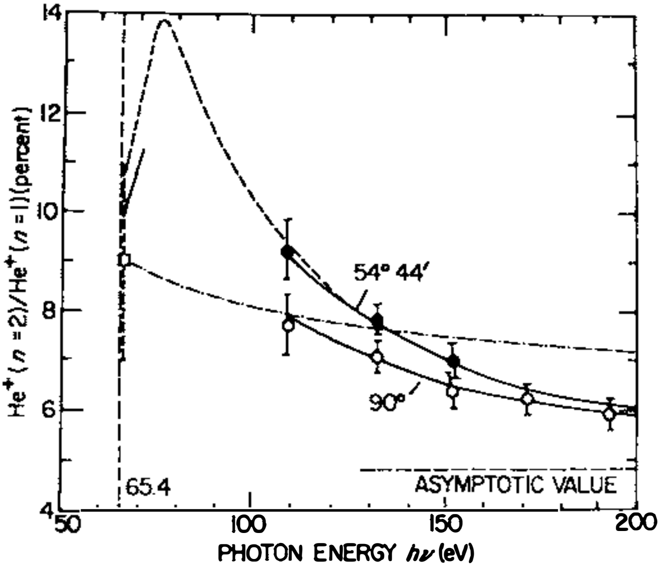


FIGURE 1.8. The ratio of the cross sections for photoionization of helium with excitation of He$^+$ to the n = 2 level and ordinary photoionization. The points, measured at two different ejection angles, are compared with theoretical curves showing major discrepancies.

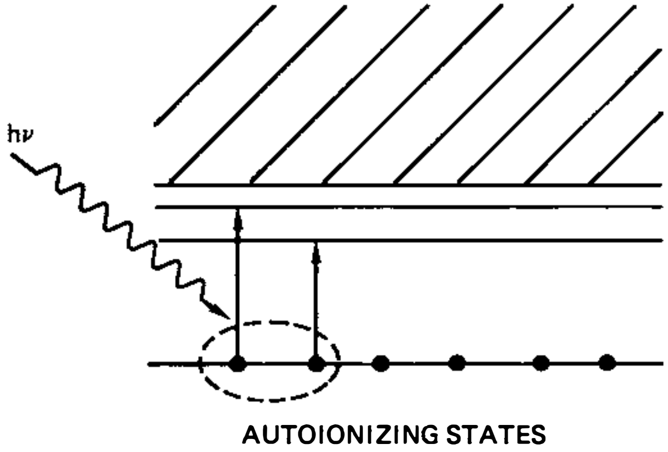


FIGURE 1.9. Photoexcitation of an autoionizing state.

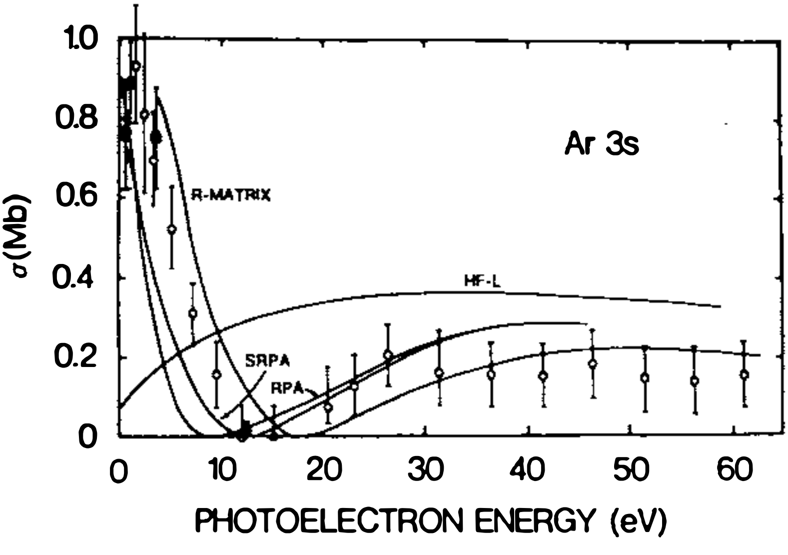
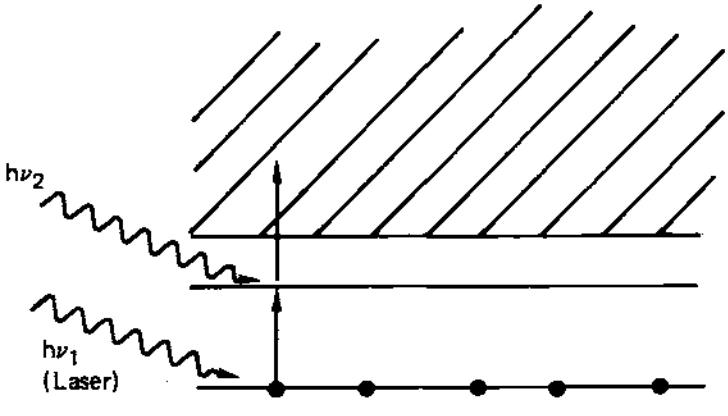


FIGURE 1.10. Photoionization cross section of Ar 3s showing experimental points, single channel theory (HF - L) and multichannel theory (RPA, SRPA, R-matrix). Note the agreement of experiment with multichannel theory which changes the cross section both qualitatively and quantitatively by including the interchannel interaction with the open 3p photoionization channel (having a cross section of tens of Mb).



PHOTOIONIZATION OF
EXCITED STATES

FIGURE 1.11. Photoionization of excited states using a laser plus another photon source.

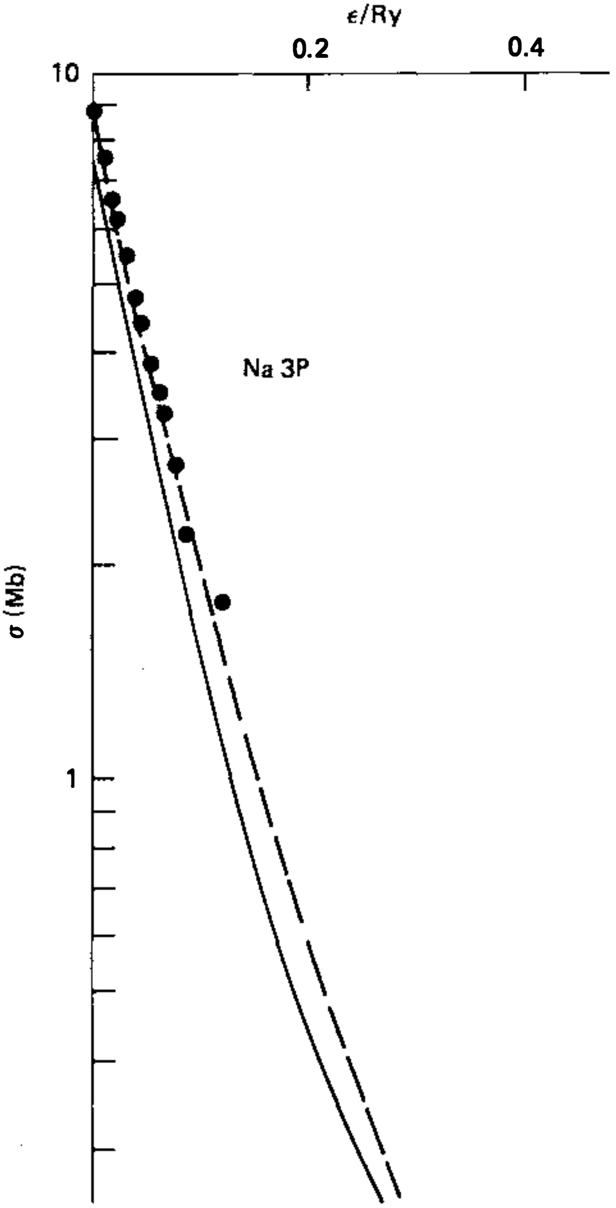


FIGURE 1.12. Comparison of experiments (points) and theory (curves) for the photoionization cross section of the 3p excited state of Na.

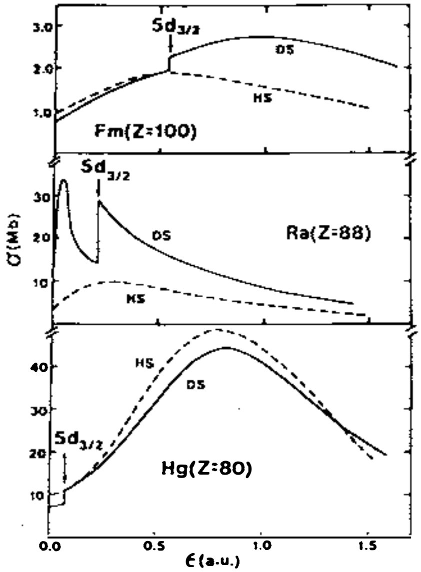


FIGURE 1.13. Theoretical 5d photoionization cross sections comparing nonrelativistic (HS) and relativistic (DS) calculations, thus highlighting the influence of relativistic effects.

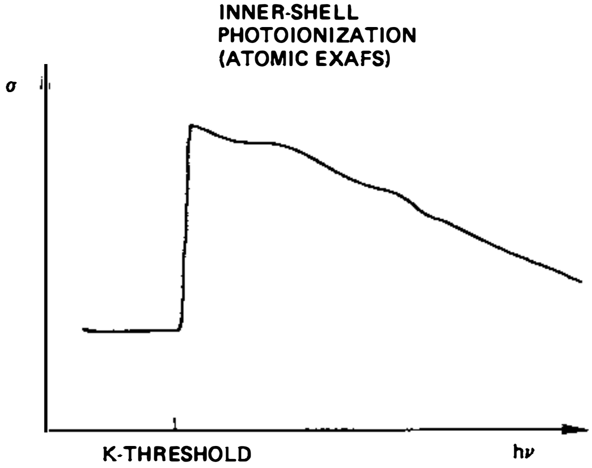


FIGURE 1.14. Schematic inner shell photoionization cross section displaying the atomic EXAFS predicted by theory.

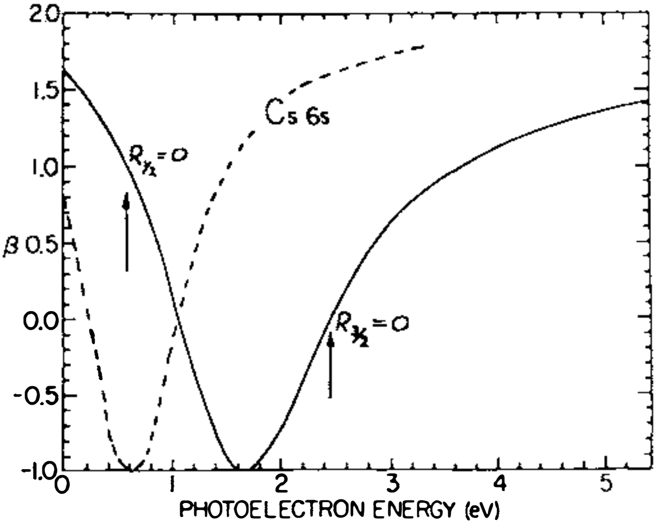


FIGURE 1.15. Photoelectron angular distribution parameter, R , for Cs 6s; the solid curve is theory and the dashed is experiment. The arrows show where each of the (theoretical) dipole matrix elements vanished. Experimentally, these zeros come at lower energy.

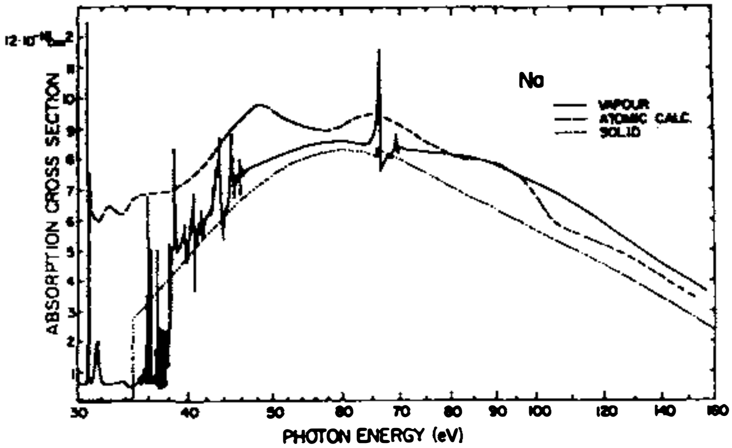


FIGURE 1.16. Comparison of experimental photoabsorption cross sections for sodium vapor and solid along with the results of an atomic calculation. Note the similarity of all three.

2. PROPERTIES OF SYNCHROTRON RADIATION FROM BENDING MAGNETS, WIGGLERS, AND UNDULATORS

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Electrons in circular motion at low velocity emit radiation in a nondirectional pattern as shown in Figure 2.1a. At velocities approaching the velocity of light the radiated power increases dramatically and the pattern is folded forward into a cone with a full opening angle given approximately by $2\gamma^{-1} = 2 m_0c^2/E$ as shown in Figure 2.1b. This angle is only 1 mrad for a 1 GeV electron and correspondingly smaller for higher electron energy. Thus, synchrotron radiation is exploited differently when the source is a bending magnet, a wiggler, or an undulator.

BENDING MAGNETS

Bending magnets produce a large horizontal fan of continuum radiation, much larger than γ^{-1} and much larger than the acceptance of an experiment. The vertical opening angle remains small. Collecting optics can increase the flux delivered to an experiment by accepting a horizontal angle greater than $2\gamma^{-1}$, but the brilliance is not increased (see Figure 2.2a).

WIGGLER MAGNETS

A wiggler magnet is a device with several poles which produces one or more oscillations of the electron beam but no net deflection or displacement of the beam. The deflection angle in each pole is large compared to γ^{-1} (see Figure 2.2b). The spectrum produced by a wiggler is similar to that produced by a bending magnet; i.e., a rather smooth continuum, although there can be interference peaks, particularly at long wavelengths.

Wiggler magnets may be inserted into storage ring straight sections and can produce beams with a wide range of spectral and geometrical properties. The simplest wiggler produces a single oscillation of the electron beam, and the central pole generally has a higher magnetic field than the ring bending magnets, resulting in a hardening of the spectrum. Such single oscillation wigglers (also called wavelength shifters) with superconducting fields up to 6 T are in operation at the Daresbury SRS and the Photon Factory in Tsukuba, Japan. In Novosibirsk, USSR, a 3.5-T superconducting wiggler with 20 poles has been used on the VEPP-3 ring. The Japanese wiggler employs a horizontal magnetic field, causing the electron beam to execute a vertical oscillation, producing a vertically polarized synchrotron radiation beam. The fan from single oscillation wigglers is usually very large (several degrees) and the beam is easily shared by several experimental stations. For example, the SRS wiggler will serve 7 simultaneously operational x-ray stations.

Six pole electromagnet wigglers are in operation at Frascati and Cornell and two 8-pole electromagnet wigglers are in operation at Stanford. These devices have peak fields of 1.8-1.9 T. In 1984 a 54-pole permanent magnet wiggler with a peak field of 1.2 T began operation at Stanford producing a very intense and very narrow (about 2 mrad wide) beam. Permanent magnets offer the possibility to construct short period devices with fields up to about 2 T. This technology is likely to be extremely important for future wiggler and undulator applications. In particular the new hybrid approach developed by K. Halback of Lawrence Berkeley Laboratory extends capabilities to produce short period, high field devices.

Wigglers now in use produce total radiated power up to 3 KW and power density on beam line components up to about 5 KW/cm^2. New designs for beam line components have been developed to handle these thermal loads. Proposed new rings will present even more severe thermal problems because of the higher electron energy, longer straight section length, and lower emittance. Because of this, undulators with their quasi-monochromatic spectrum and larger number of useful photons per unit of total radiated power appear attractive.

UNDULATOR MAGNETS

An undulator magnet is a multipole device with N periods in which each pole produces a deflection of the order of γ^{-1}, the natural emission angle of synchrotron radiation (see Figure 2.2c). Thus the intrinsic high brilliance of the radiation is preserved and enhanced. Furthermore, interference effects in the radiation produced at many essentially colinear source points results in a modified spectrum with tunable quasi-monochromatic peaks at wavelengths given by $\lambda \sim \lambda_u/\gamma^2$ and harmonics. This further enhances the brilliance at these wavelengths. If the electron beam angular divergence is $< \gamma^{-1}N^{-1/2}$, the on-axis brilliance produced by an undulator increases as the square of the number of undulator periods. Thus in new low emittance rings it should be possible to get 3-4 orders of magnitude enhancement in brilliance (compared to ring bending magnets) from undulators with about 100 periods.

Permanent magnet undulators are in use at the NSLS VUV ring, the Photon Factory, and SPEAR and are being built for other rings such as PEP. Although undulators on present rings offer higher brilliance than bending magnets, the full potential of undulators is reached only at lower emittance than is available in present rings. Undulators provide lower energy photon beams than bending magnets and wigglers, leading to the need for higher electron energy to extend their spectral range.

Figure 2.3 shows a comparison of the brilliance that would be produced by bending magnets, wigglers, and undulators in the low emittance 1.3 GeV Advance Light Source proposed by the Lawrence Berkeley Laboratory.

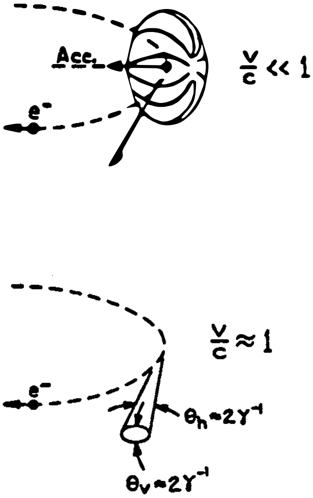

FIGURE 2.1a-b. Electrons in circular motion in a nondirectional pattern.

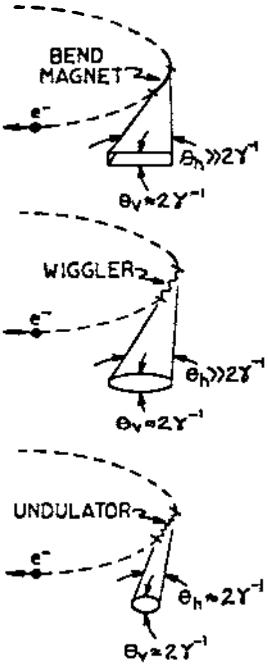

FIGURE 2.2a-c. Magnets.

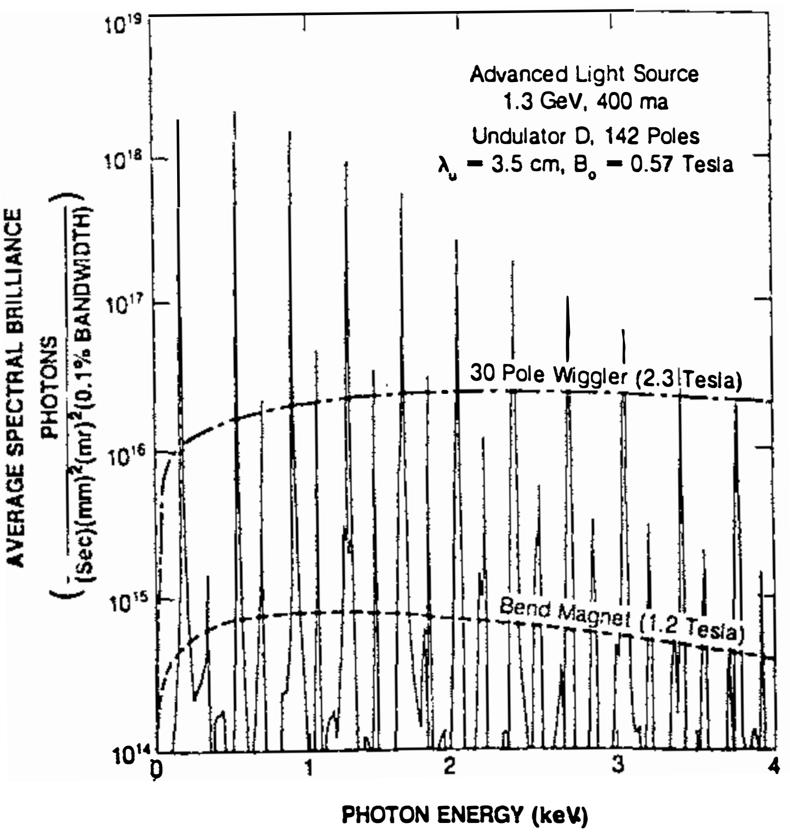

FIGURE 2.3. Comparative brilliance of magnets.

3. PARTIALLY COHERENT X RAYS FROM MODERN STORAGE RINGS

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The soft x-ray and vacuum ultraviolet spectral regions (collectively the XUV), extending from photon energies of several electron volts (eV) to several thousand electron volts (KeV), are rich in atomic and molecular structure. The regions include primary resonances of carbon, oxygen, and nitrogen, which are important to fields as diverse as biology and microelectronics, as well as myriad molecular resonances. Although previously of limited access to all but a few specialists, the XUV region is now experiencing a renaissance which will open it to a broad class of life, physical, and industrial scientists.

Recent review articles[1] describe significant progress in the development of x-ray optical techniques, such as focusing lenses, interference coatings, normal incidence mirrors, picosecond detectors, thin window materials, and so forth. In addition, there is great progress being made in the development of coherent radiation sources,[2] which will permit the extension of phase sensitive techniques to this interesting spectral region. These new sources will provide new capabilities for achieving high photon flux levels with narrow spectral widths, picosecond time structure, polarization control, and the ability to point and focus to small sample volumes.

The ideal source of soft x rays is one of full coherence, and high peak or average power as dictated by applications. Full coherence implies a line width limited only by temporal pulse duration and a perfect phase front (as from a "diffraction limited" source). Several routes to the development of such ideal soft x-ray sources are now being actively pursued. These include atomic lasers, free electron lasers (FELs), and storage ring (synchrotron) undulators. For short wavelength (XUV) applications, FELs and undulators are very closely related, each being dependent on the development of all controlled (low" emittance") electron storage rings, with energies of the order of 0.5 to 1.5 GeV beam energy, and many period magnetic structures, referred to as undulators. The major thrust of this article is that undulators provide the only sure route to coherent soft x rays in the near term, that they are tunable throughout the region of interest, and that they will serve a multitude of users, in disparate fields of science and technology, albeit at a large central research facility.

Figure 3.1 illustrates interesting atomic and molecular transitions that might be utilized to pursue a variety of scientific ends in the pure and applied sciences. Shown in the upper left is the extent to which coherent radiation sources (klystrons, lasers, etc.) are available. Note that they do not extend significantly beyond 1000Å. Incoherent x-ray sources, particularly broad-band synchrotron radiation facilities, are shown in the lower right. The large block in the overlap region shows the extent to which partially coherent undulators could be utilized to bridge this gap.

Figure 3.2 illustrates the production of coherent undulator radiation by a very fine pencil like beam of relativistic electrons traversing a periodic permanent magnet structure. The radiation wavelength is relativistically contracted from centimeter magnetic period lengths to x-ray wavelengths and appears in a very narrow radiation cone of angular width typically 100 μrad. As observed in the forward direction, undulator radiation is largely coherent in nature--appearing to come from a near diffraction limited source (small area times solid angle product), and having a narrow spectral width, on the order of $\lambda/\Delta\lambda \simeq N$. Figure 3.3 shows the sharp spectral features of a proposed undulator, as well as the spatial radiation pattern 10 m from the source.

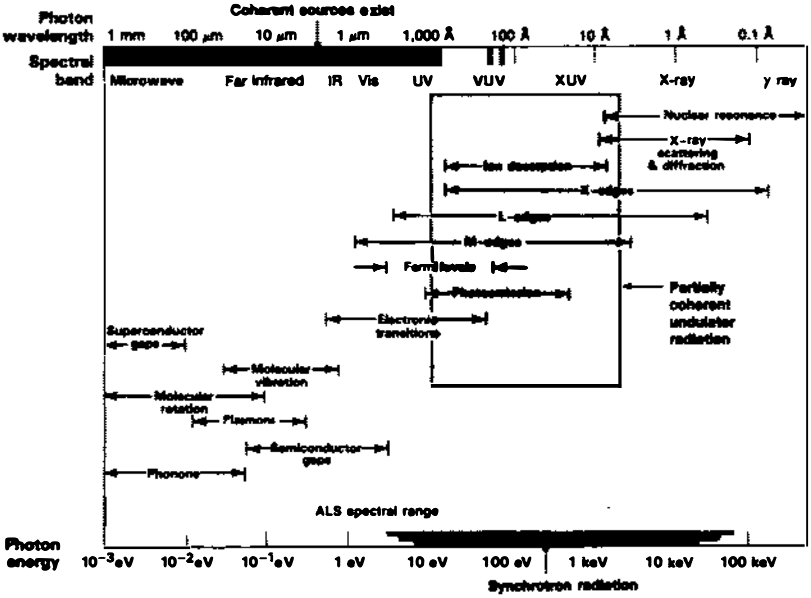

FIGURE 3.1. Coherent sources currently extend to about 1000Å. Incoherent synchrotron radiation sources currently cover the x-ray region. Undulator radiation, at the next generation storage rings, will provide a much needed source of partially coherent radiation in the important soft x-ray and VUV spectral regions.

Figure 3.4 shows a comparison of undulator and laser techniques in terms of average coherent power, that is the power radiated with full spatial coherence, and a longitudinal (temporal) coherence of 1 µm (micron) or longer. Note that only undulators are able to provide coherent radiation in the important soft x-ray region. Atomic and molecular lasers, as well as laser harmonic and mixing techniques, are primarily limited to wavelengths of the order of 1000Å. Exciting new results at Lawrence Livermore[3] have now demonstrated lasing techniques to the 200Å region, and we anticipate that these will be extended somewhat below 100Å. These devices will likely reach higher peak power at some point, provide relatively narrow spectral width ($\lambda/\Delta\lambda \sim 10^4$), but will not necessarily possess full spatial coherence, and so are also partially coherent in nature. Other laser techniques,[4] of significantly smaller scale, are likely to appear in the several 100Å region over the coming years.

In summary, we see an important role for undulators as next generation storage rings in the coming years. Undulators will provide partially coherent x rays, at wavelengths to 10Å and beyond. Undulators are tunable, will be available to a broad array of scientific groups, and importantly, will provide radiation of full spatial coherence, full polarization control, and picosecond time structure.

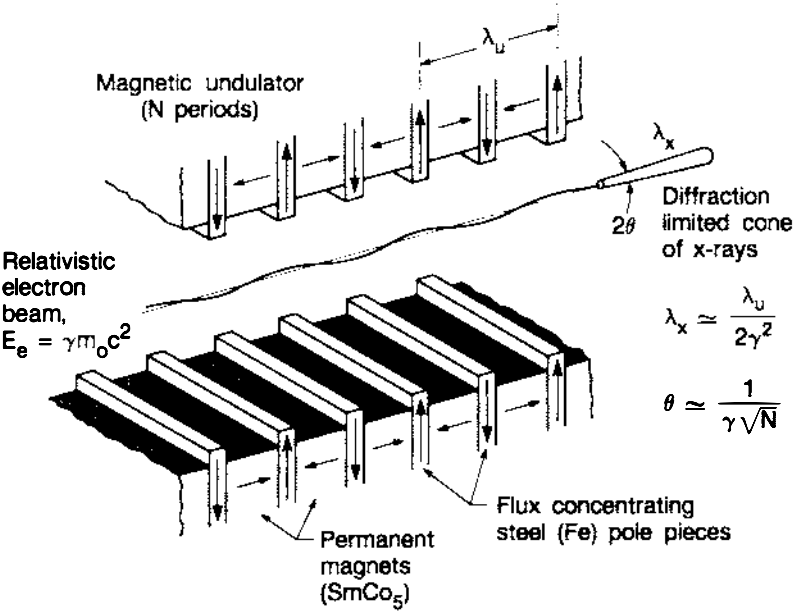

FIGURE 3.2. Pencil like beams of relativistic electrons produce spatially coherent x rays of relatively narrow spectral width, $\lambda/\Delta\lambda \simeq N$, when traversing a periodic magnetic undulator.

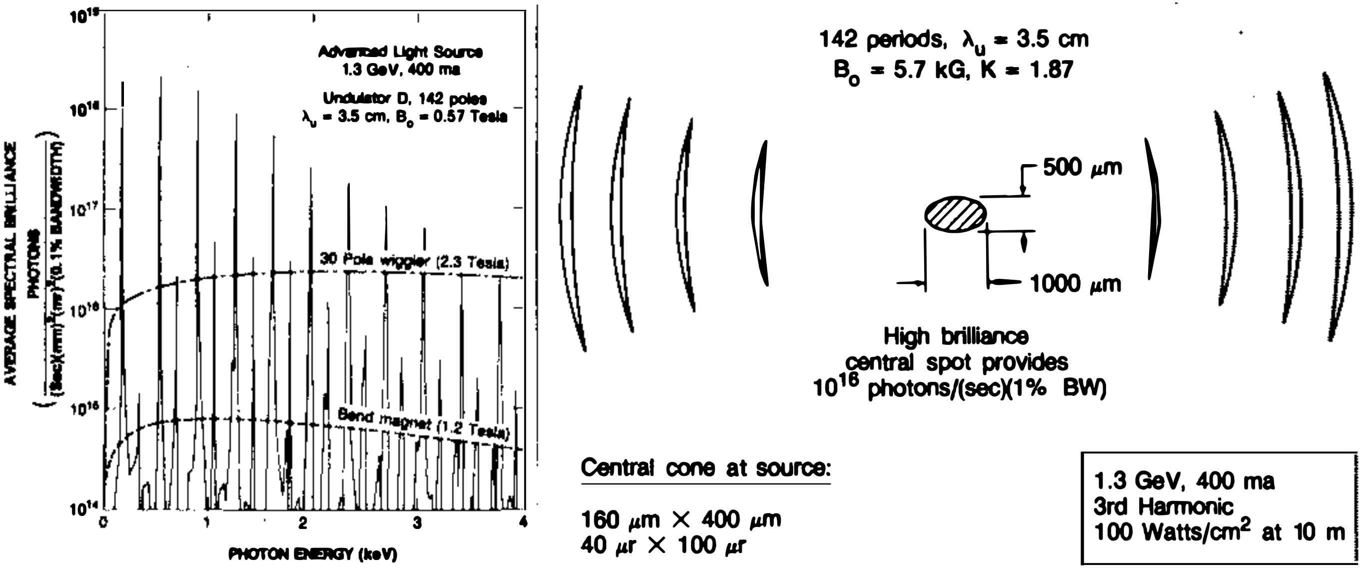

FIGURE 3.3. Spatial and temporal radiation calculated for soft x-ray undulator on the proposed Advanced Light Source at Berkeley.

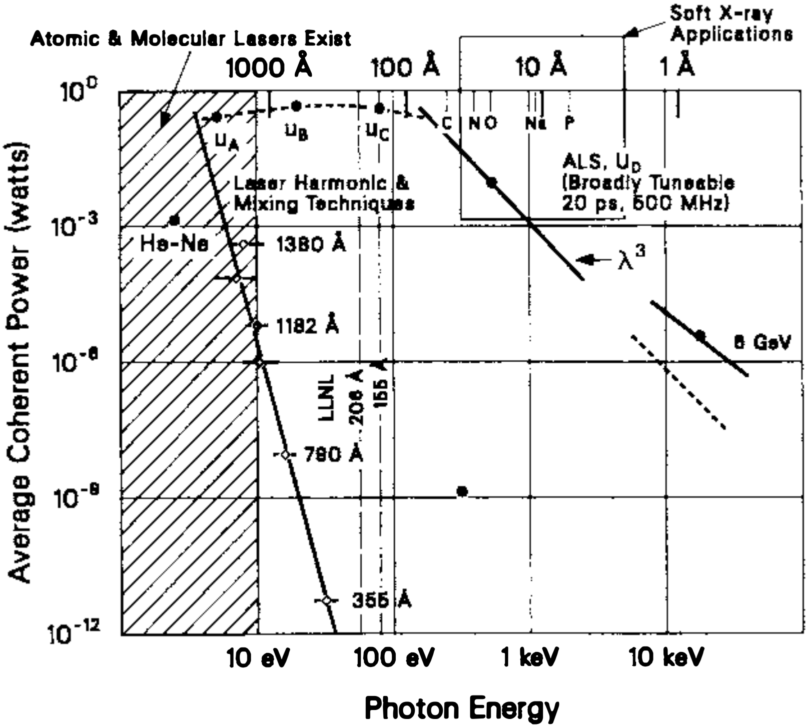

FIGURE 3.4. Partially coherent undulator radiation will be available at wavelengths throughout the VUV and soft x-ray spectral regions at the next generation storage ring facility. With feedback mirrors, or very long undulators, these facilities will eventually provide the first XUV free electron lasers. Atomic and molecular lasers, as well as laser harmonics and mixing techniques, are shown for comparison.

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4. LASERS IN THE VACUUM ULTRAVIOLET AND X-RAY REGION

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ABSTRACT

A basic problem in laser technology is the generation of coherent energy in the vacuum ultraviolet, the extreme ultraviolet, and the x-ray regions. Recent research findings strongly support the conclusion that the physical and technological elements necessary to create the conditions for amplification in these spectral regions are now available. The experimentally normalized scaling law for the short wavelength laser technology projects an average spectral brightness at 1 kV quantum energy, which is a factor of approximately ten thousand-fold higher than any other alternative known. If the laser-based approaches for short wavelength generation that are currently being developed meet their goal, a new and unusually cost effective technology will be available for scientific and industrial applications of x-ray sources.

INTRODUCTION

The wavelength of x rays is close to the atom-atom separations in normal solid matter. Because x rays can penetrate condensed materials, they provide a versatile, natural and convenient yardstick for visualizing the basic microstructure of all solid materials. Since knowledge of this microstructure is of fundamental importance to several scientific and industrial areas, sources of radiation in the x-ray region are in very high demand. Major areas of application include basic materials research, electronic microstructures, biology, microscopy, genetics, and catalysis.

Figure 4.1 [1-22] illustrates relevant data for several important applications. Two important features are immediately apparent. They are (1) the rather broad range of useful wavelengths and (2) the rapid expansion in the range of applications that occurs just above a quantum energy of ~ 100 eV. Due to the basic nature of the wavelength interaction of x rays with condensed matter, it is natural that applications involving the solid state, such as microstructure measurement and surface analysis, are prominent.

LASER-BASED APPROACHES FOR X-RAY GENERATION

A basic and long-standing problem in the field of coherent sources of radiation is that associated with the generation of coherent energy in the short wavelength range including the vacuum ultraviolet (VUV), the extreme ultraviolet (XUV), and the x-ray regions. The scale of difficulty involved in generating amplification at a quantum energy of 1 kV is apparent from the general requirement, established by basic physical reasoning, calling for the creation of extraordinary specific power densities, on the order of 10^{14} W/cm^3, in a carefully controlled way.

Nominally, spectrally bright coherent sources of wavelengths λ in the range $0.1 < \lambda \leq 100$ nm are desired. It is generally understood[23,24] that (1) a high power state-selective (high effective brightness) source of excitation and (2) an appropriate physical coupling mechanism are the key requirements for the successful creation of the conditions for amplification in the VUV, XUV, and x-ray ranges. These basic conditions are common to all approaches. The general lack of amplifying media at wavelengths shorter than approximately 100 nm is, therefore, directly attributable to the absence of these two essential factors working in concert. It is of primary significance that the results of physical studies conducted over the last few years strongly indicate that these two necessary elements are now available.

A simple schematic of a laser-based instrument for x-ray generation is shown in Figure 4.2. Several technological choices and approaches are available for components 1, 2, and 3. For component 1, various types of discharges, electron beams, and available lasers are alternatives currently undergoing evaluation. A group at Stanford University[25] is using a laser-plasma approach to generate ionizing radiation, which subsequently serves to excite the medium. Another research effort at the Princeton Plasma Physics Laboratory[26] is developing a technique based on recombining plasmas originally produced by intense infrared laser radiation. The Livermore National Laboratory[27] is examining a class of media arising from plasmas formed by laser irradiation of thin films. In the work[28] at the University of Illinois, we have selected an approach, which in addition to the energy density requirement, utilizes the coherence obtainable from laser sources serving as component 1. In this case, direct excitation of the amplifying medium is produced through coupling arising from special physical mechanisms,[29] which have been found to occur at extremely high radiative intensities.

SCALING RELATIONSHIPS FOR X-RAY SOURCES

Since the quality of technologies serving as x-ray sources can be placed on a simple numerical scale, a general comparison of the laser approach to available options is readily performed. One relevant comparison is based on average spectral brightness per unit cost. Brightness is significant, since it is the physical measure of the ability to deliver x-ray energy to a given spot in a given time at a defined wavelength λ. Generally, greater brightness translates, in direct proportion, into greater quality and utility of the radiation. Therefore, for many applications, the unit cost of brightness is equivalent to the unit cost of utility. Figure 4.3 illustrates the basic character of this comparison.[30] The framework of a simple and general physical model with conservatively stated assumptions, the scaling law for the brightness of the laser-based approach, can be shown to vary as λ^{-2}. This relationship serves to establish the slope of the dashed contours on Figure 4.3. Two lines with this slope have been normalized with experimentally observed[31,32] sources using hydrogen (H_2, 117 nm) and krypton (Kr, 93 nm), thus, defining a band for the locus of the projected laser technology. This band, then, represents a crystal ball that reveals the expected trend for the future. Note that the midpoint of this region, at a quantum energy of 1 KeV (λ = 1.24 nm), is approximately a factor of ten thousand above all the alternatives, either present or projected. Significantly, since the derivation approximately one year ago[30] of the anticipated scaling behavior of the laser-based technology illustrated in Figure 4.3, a result has been obtained by the group at the Livermore National Laboratory[27] that furnishes an important test of our ability to correctly forecast the future course of this field. The experimental datum representing the findings at Livermore,[27] which demonstrated amplification at 20.6 nm, has been placed on Figure 4.3 and is indicated by the point designated as Se^{24+}. We observe that this point lies almost in the center of the field previously established for the projected scaling.

The region in the lower portion of Figure 4.3 refers to the domain served by synchrotron technology. Currently, synchrotron technology is the only practical alternative to the laser approach. The upper boundary is the recently proposed Advanced Light Source (ALS), and the lower limit is defined by the parameters of the currently operating National Synchrotron Light Source (NSLS). This level of performance should be contrasted to the diagonal region near the top representing the projected operating region for laser technology. A comparison based on peak rather than average brightness would increase the gap between these technologies, for the cases shown, by another factor of approximately one million. Moreover, because of the relative simplicity and smaller scale of the laser method, the cost of that approach is estimated to be in the vicinity of one percent of the synchrotron technology. Such a technical development, by increasing the average brightness per unit cost by a factor on the scale of one million and the peak brightness per unit cost by approximately one trillion, would certainly cause profound changes in both the availability and use of short wavelength radiation (x rays). The overall message contained in Figure 4.3 is that, if the laser developments can successfully continue to proceed along the scaling band shown down to quantum energies in the kilovolt range, then they will clearly represent the superior technology by an enormous margin.

CONCLUSIONS

New laser-based approaches for x-ray generation are currently being developed. If this general method of development is successful in meeting its goal, a new and unusually cost effective technology will be available for scientific and industrial applications of x-ray sources. This technology, perforce, would serve an unusual range of important applications concerning the microcharacterization of solid matter. In comparison to alternative methods for the generation of radiation in the x-ray range, on the basis of performance per unit cost, the laser-based technology envisaged is projected to represent a minimum improvement of approximately one millionfold.

Recent research developments strongly suggest that we are now at a propitious stage for rapid advance of the laser-based technology. No fundamental barrier exists preventing its development, and physical technologies are available that can produce the conditions necessary for its operation. If this view is correct, current levels of support for the disciplines involved are insufficient to sustain the pace of activity both possible and desired. Among the relevant scientific areas is a substantial number of topics normally considered under the general heading of the physics of atomic collisional and radiative phenomena. For full advantage to be derived from this circumstance, a significant increase in the resource base over the next 3- to 5-year period is indicated.

A summary of the potential significance can be stated in the context of biology. As a physical technology for basic measurement, the x-ray laser would be unsurpassed in its ability to see the properties of living matter. If achieved, how would this outcome fit within the historical pattern that has evolved with the use of basic physical techniques of measurement in the field of biology? The invention of the light microscope in the seventeenth century marked an enormous advance in the ability to perceive the living world on a small scale. Indeed, the field of bacteriology developed as a direct consequence. Most significant, however, was the philosophical sea change in world view motivated by these observations that transpired as man began to realize his position of competition with and dependence upon this newly revealed and far older microworld. The second major advance occurred shortly before World War II with the use of the electron microscope, a device invented around 1930, to furnish man's first view of a virus. The x-ray laser, if it can be developed, will enable us to directly visualize the molecular society inside living organisms, essentially on an atomic scale. With this kind of truly revolutionary vision, it is very hard to believe that new, important, and fundamental insights paralleling the discoveries of the past will not develop.

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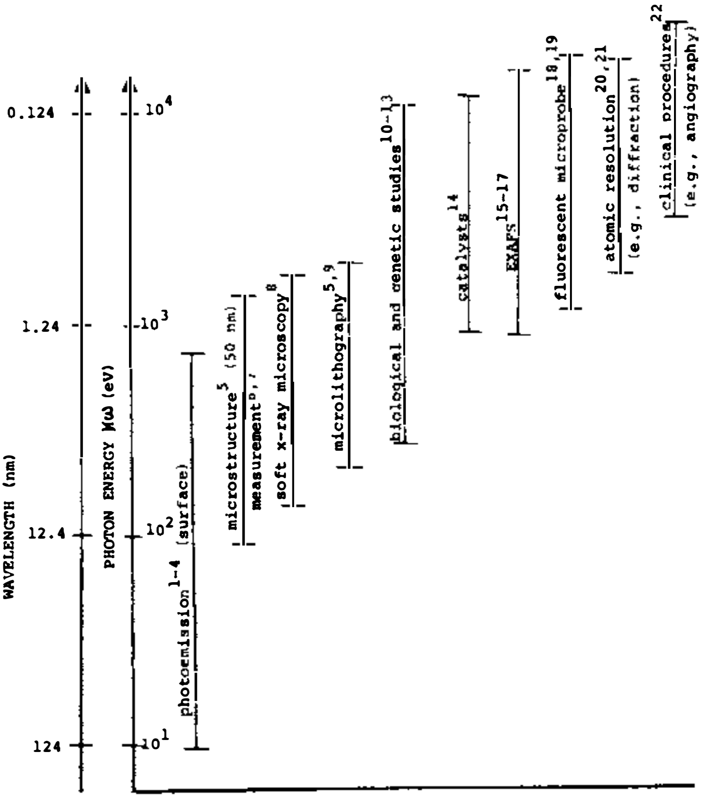

FIGURE 4.1. Wavelength regions serving a range of specific applications involving short wavelength instrumentation.

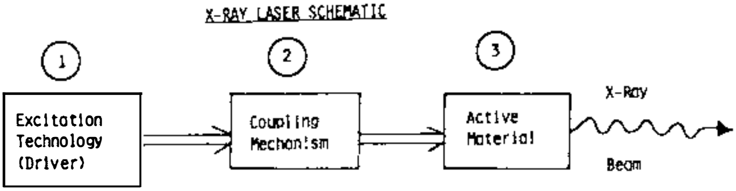

FIGURE 4.2. Simple schematic of laser-based approach to x-ray generation. Element (1), the driver technology for excitation; element (2), the coupling mechanism, serves as the essential "connecting rod" enabling the energy available from (1) to be properly channeled to the active material (3) which generates the x-ray beam.

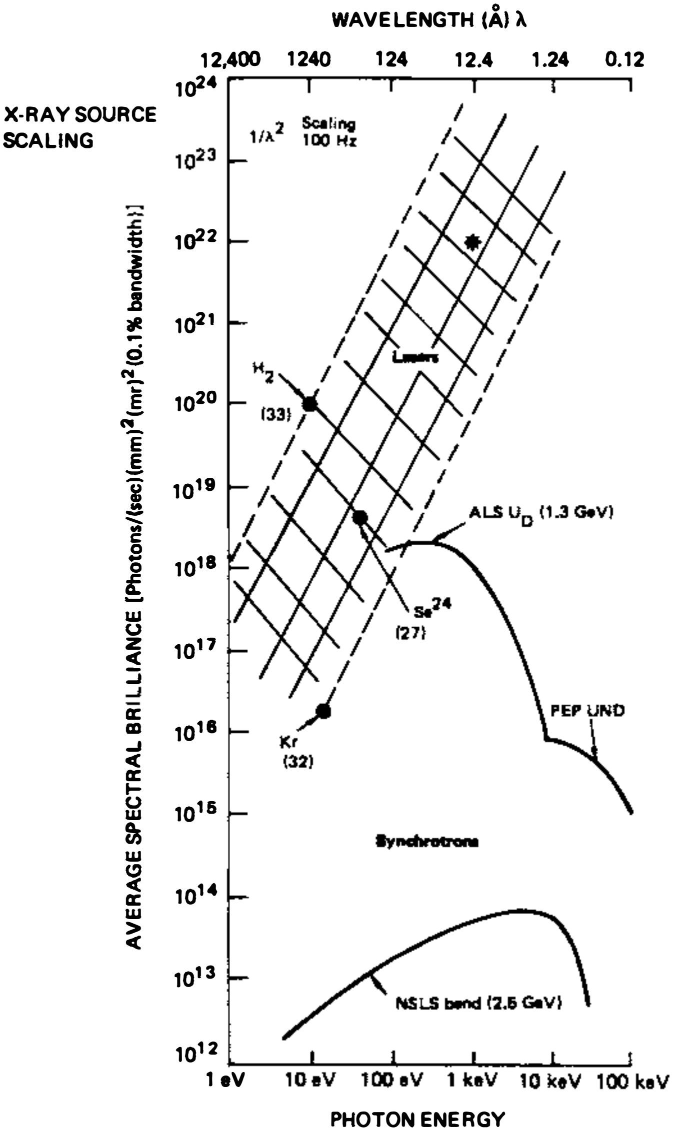

FIGURE 4.3. Comparison of projected performances of synchrotron and laser technologies for the production of short wavelength radiation. The laser approach is assumed to have a 100 Hz pulse rate. See discussion in text. The experimental points, H_2, Kr, and Se^{24+} carry designations of the appropriate references in parentheses.

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5. LASER PRODUCED PLASMA LIGHT SOURCES

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ABSTRACT

Radiation from laser produced plasmas has been shown to be an efficient source in both the extreme ultraviolet (XUV) and soft x-ray regions of the spectrum. The XUV radiation can be produced as a clean continuum between 10 eV and 300 eV with efficiencies > 5 percent. Generation of x rays as a mixture of lines and continua can be achieved with ~10 percent efficiency for generation of .7-20 keV radiation. Laser produced plasma sources complement synchrotron radiation sources in that they have high peak fluxes but lower average intensities. Laser plasma sources can be run in a variety of environments and in many cases provide a modest cost, portable source of highly controllable and reproducible radiation.

INTRODUCTION

Hot plasmas have been the major laboratory source of intense radiation in the visible and ultraviolet throughout the period characterized as modern physics. This is especially true for radiation in the extreme ultraviolet (XUV) below 100 nm where the blackbody temperature necessary to produce appreciable radiation exceeds the boiling point of the most refractory materials. The traditional approach has been either to run a discharge in a gas or to strike an arc between two electrodes so that the discharge runs through the vaporized material. In either case a plasma with a high electron temperature (1-20 eV) can be obtained. The electrical plasma discharges are well treated in Sampson's book on vacuum ultraviolet spectroscopy[1]. In recent years synchrotron radiation light sources have played a major role in extreme ultraviolet physics. However, these sources exist as facilities rather than traditional laboratory light sources. Furthermore, they complement rather than compete with plasma sources in that they are continuous sources of high average brightness while plasma sources at short wavelengths are pulsed with high peak brightness.

Electrical discharge plasmas are limited in the amount of energy that can be deposited in a small volume in a minimum time, which limits the maximum temperature in the plasma. It was realized very early that the extremely high brightness of pulsed lasers provides an ideal mechanism for heating plasma sources. Ehler and Weissler[2] used a Q-switched ruby laser of 100 MW peak power to study the VUV radiation from various target materials. Since that time the spectral region of study has been extended into the x-ray regime while the powers available have been raised several orders of magnitude. The aim of this paper is to give a brief, but by no means exhaustive, summary of the status of laser plasmas as extreme ultraviolet (XUV) and x-ray light sources.

NATURE OF LASER PLASMA SOURCES

Laser produced plasma light sources are generally solid targets that are vaporized and heated by intense, short duration, focused laser beams. Liquid Hg has also been used to provide self healing, long lived targets[3]. Incident power densities vary from 10^{11} Wcm^{-2} to 10^{16} Wcm^{-2} and the dense plasma is heated by inverse

Bremsstrahlung and radiates by Bremsstrahlung, recombination, and line emission. The sources themselves are simple metal rods or foils and the size, expense, and portability of the system are determined by the properties of the lasers. For XUV radiation the laser can be a Nd:YAG system of modest cost and sufficiently portable to be carried from laboratory to laboratory as the need arises. For the most intense x-ray sources large kilojoule lasers in fixed facilities are used. Intermediate sized systems such as slab glass or excimer lasers should provide sources of x rays to $\geq$ 2 keV at a cost and complexity that is appropriate for small laboratories as opposed to facilities.

The radiation from laser produced plasmas varies from very pure continuum emission to predominantly line sources depending on the choice of target material and the spectral region of study. The plasmas are very high intensity, pulsed sources of low duty cycle with a pulse duration determined by the driving laser down to $\leq 10^{-10}$ sec duration. The radiation is unpolarized and nearly isotropic and is highly reproducible. Although the radiant power produced is comparable to that produced by synchrotron radiation sources, the very different output parameters make comparisons of the sources difficult and the two sources in fact are complementary rather than directly competitive.

One particularly useful feature of laser plasma sources is the absence of any requirement for high vacuum conditions. Sources are easily run with an atmosphere of 100 torr of background gas or more with no apparent effect on the emission. Thus He can be introduced into the source chamber to absorb much of the XUV radiation while transmitting the soft x-ray output.[3,4] Similarly, laser plasma sources have been inserted into atomic vapors and used in situ as sources of ionizing radiation for pumping metastable ionic systems.[5] In general, the sources are compatible with most conditions which are consistent with the use of XUV or x-ray radiation.

SOURCES OF RADIATION $\leq$ 300 eV ($\geq$ 4 nm)

Intense sources of radiation in the XUV (10-300eV) can be produced with laser intensities of 10^{11} to 10^{13} Wcm^{-2}. Although some experiments have been performed with 10.6 μm radiation, most work to date has been done with 1.064 μm and .694 μm sources. It is expected that excimer sources from 200 nm to 350 nm will also prove to be useful drivers. Typical driving laser energies range from 10 J in 20 ns for ruby and Nd:glass systems to 1 mJ in 10 ps for mode locked Nd:YAG lasers. With the use of Nd:YAG lasers the repetition rates are typically 10 Hz with pulse duration of 10^{-11}-10^{-10} sec for mode locked lasers and 10^{-8} sec for Q switched lasers. The radiating source size varies from < 50 µm for tightly focused, mode locked beams to ~.2-.5 mm for longer duration pulses. The VUV output rises linearly with the incident laser energy at lower values and shows signs of saturation at higher energies. This feature means that the stability and reproducibility of the VUV output is at least as good as that of the driving laser.

If targets of low to moderate Z are used, then the emitted radiation consists of recombination and Bremsstrahlung continua with intense line spectra superposed. In recent years it has been shown that if high Z targets are used then the complexity of states of the partially stripped ions produces such a multitude of lines that they merge into regions of continua that modulate the underlying recombination continua.[6] The result is not only an extremely clean spectra, essentially line free for as much as 300 eV, but a concentration of intensity in limited regions of the XUV (see Figure 5.1). The regions of intense emission can be varied by varying the target material. The production of line free continua has been shown to be greatly enhanced by observing the source with focusing optics, which select out the high density, high temperature core of the radiating plasma.[7] Calibration studies of laser plasma XUV sources are still under way but measurements of the absolute intensity of the sources indicate absolute conversion efficiencies from the driving radiation to blackbody radiation in excess of 5 percent.[5]

The use of high repetition rate lasers allows the construction of light sources that for many purposes are quasi-continuous. The irradiation of the target causes rapid erosion of the material as a crater is focused, the rate of erosion depending sensitively on the target material, but the area of damage is comparable to the laser spot size. Targets can be mounted on a rotating threaded shaft that presents fresh material to the laser after a fixed number of shots.[8] For systems that erode more slowly, such as W or Cu, 10 or more shots can be made at each position and it becomes feasible to construct a compact system that would run 10^6 shots before changing target material. An alternative approach has been demonstrated by Jopson et al.[3] where liquid Hg was used as the target material so that there was no cumulative target damage. A more serious problem for multiple exposures is the accumulation of spattered debris on optics and other surfaces. Incoming laser surfaces can be shielded by use of movable thin plastic films but this is obviously not feasible for regions exposed to XUV radiation. Kuhne et al.[4] and Carroll et al.[6] showed that laser plasmas can be operated with an ambient background gas that transmits the radiation of interest and Jopson et al.[3] used a He background pressure to protect their optical system from spattered Hg from their target.

SOURCES OF RADIATION $\geq$ 300 eV

The use of moderate power lasers ($\leq 10^9$W) is a convenient source of emitting plasmas but the electron temperatures are typically less than 100 eV.[9,5] The output for a 100 eV blackbody peaks near 200 eV and outputs fall rapidly at higher energies. For the production of x-ray photons it is necessary to go to larger power densities associated with very high energy, short pulse lasers, which are usually associated with national laboratories, both here and abroad, and some large industrial efforts. The x-ray emission has been studied with sophisticated diagnostics and computer modeling capabilities so that it is better understood than the XUV radiation. The spectrum is predominantly free-free and free-bound radiation combined with a simple line spectrum. The heating mechanism for these high power lasers is inverse Bremsstrahlung, which typically produces a hot, dense plasma with a density around 10^{21} cm^{-3} and an electron temperature of 300 eV to 500 eV. The plasma is characterized by transient stages of ionization before the ionization stages come to equilibrium. During subsequent times there is rapid ion movement because of expansion. The preponderance of electrons are Maxwellian and provide radiation of a few keV[10]. There is generally also a tail of hot electrons with energies up to several keV with radiation produced out to 350 keV[11]. An experimental and theoretical study of laser plasmas with high time resolution has recently been reported by Nakano and Kuroda.[12] Their work not only covers the features mentioned above (except for the hot electrons) but also explains the strong dependence of electron temperature, and subsequent soft x-ray emission, on the Z of the target material.

Several studies have been made of the absolute conversion efficiency from laser input energy to x-ray photons. Matthews et al.[10] of Lawrence Livermore Laboratories have made such measurements with 1.06 μm, 0.53 μm, and 0.35 μm radiation using intensities between 10^{14} and 10^{16} W cm^{-2} with durations between 10^{-10} and 2 x 10^{-9} sec. Targets of Al, Au, Ti, Ni and Zn were used, generating intense radiation between 2 and 10 keV with a strong, simple line spectrum on top of a continuum background (see Figure 5.2). The efficiency defined as the ratio of x-radiation to incident laser energy was independent of spot size (total energy) if pulse duration and intensity were constant. The efficiency decreased with increasing intensity and for Al and Ti targets was five times higher for .35 μm radiation than for 1.06 μm radiation. For intensities above 3 x 10^{15} W cm^{-2} the efficiency was constant from 10^{-10} sec to 2 x 10^{-9} sec using 1.06 radiation. For the 10^{-10} sec pulses the line output had a duration of 1.4 to 2.4 times the laser pulse duration, varying with the target, while the continuum output had approximately the duration of the laser. For 6 x 10^{-10} sec pulses the line emission followed the laser.

Yaakobi et al.[13] at the Rochester Laboratory for Laser Energetics have made similar studies but find a significantly stronger increase in efficiency in going from 1.06 μm to 0.35 μm radiation. For a constant pulse duration they report that the x-ray output depends almost exclusively and linearly on the laser pulse energy. Defocusing to decrease the irradiance by more than a factor of 10 causes a decrease in efficiency of less than 1.5. The radiation temperature of the plasma was 0.8 keV for the continuum and 2 keV for the line emission. For a glass (Si) target with a 5 x 10^{14} W cm^{-2} 5 x 10^{-10} sec driver laser the output was 2 x 10^{15} photons in the continuum and an approximately equal amount in the $1s^2$-1s2p resonance line. The efficiency into individual lines in the 1.8 to 7.8 keV region was between 0.1 percent and 1 percent into each line. Nagel et al.[14] used lasers at 10.6 μm, 1.06 μm, and 0.694 μm with 20 to 10 J in 20 ns to 40 ns pulses to study x-ray emission. The 1.06 μm laser was at least 10 times more efficient than the 10.6 μm laser. With a 40 ns pulse the x-ray intensity scaled with energy as E^n with n ~ 2.5 to 3. The maximum efficiency into the 1- to 3-keV region was 10 percent. Gilbert et al.[15] made similar studies on the effect of target material on x-ray generation. They studied 36 elements between Be and U using a 1.06 μm laser generating 28 J in 8 ns focused to 4×10^{13} W cm^{-2}. They observed an electron temperature of 365 eV with an efficiency into 0.7-20 keV photons which depended on Z but had a maximum value of 9.6 percent. The same efficiency was observed with a 1 ns laser pulse. The use of a 100 μm focal spot resulted in a 120 μm emitting region. When U was used as a target no line emission was observed superposed on the continuum at energies above 800 eV using a crystal spectrograph. Nakano and Kuroda[12] have studied x-ray emission using 2 J of 1.06 μm radiation and have also discussed the large variation of x-ray output with target Z. The atomic number for maximum output above 1 keV was shown to be a function of the laser power density, and the conversion efficiency into photons > 1 keV rose rapidly with the incident energy, reaching a maximum of 2×10^{-3} for 25 J on target. The use of microballoon targets allows the achievement of higher electron densities ($10^{23} cm^{-3}$) and temperatures (~1 keV) than the use of flat targets[13].

ABSOLUTE INTENSITIES

Laser plasma outputs are most meaningfully compared with synchrotron radiation in the XUV where both sources provide a very clean continuum of radiation. Table 5.1 lists the results of measurements of absolute intensities from laser plasmas produced using conventional Nd and ruby laser of energy ≤ 10 J. The energy range of the measured photons varies from 10 eV to 450 eV and all measurements were made using grating spectrographs and monochromators. The measurements of Kuhne et al.[17] were in situ comparisons with a synchrotron radiation source, those of Mahajan et al.[7] were in situ comparisons with a well characterized theta pinch and those of O'Sullivan et al.[18] were in situ comparisons with a calibrated standard arc lamp. The measurements of Nicolosi et al.[19] used a calibrated grazing incidence spectrometer and detector system while the oldest measurement, that of Breton and Papoular,[20] used measured and estimated efficiencies for their spectrometer and photomultiplier. The measurements have all been put in the same units and the choices of parameterization are made to allow comparison of both the peak outputs and the average values (assuming 10 Hz operation) and of the intensity and the total flux output. The conditions of focus, temporal pulse behavior, and incident angle on target are not standardized enough to make variations of factors of 2 meaningful. The values for synchrotron radiation sources are shown to give a sense of the comparability of the two sources.

The output of laser generated plasmas in the x-ray region involves strong line emission as shown in Figure 5.2 from the work of Matthew et al. at the Livermore laser facility.[10] The dependence of the x-ray output as a function of incident power density is seen in Figure 5.3 from Babonneau et al.[16] using the third harmonic of a Nd:glass laser. One particularly interesting feature of this data is the crossing of the curves near 600 eV so that in the XUV region an increase in laser power density decreases the radiant output in contrast to the behavior in the x-ray region. In addition to the thermal emission in the soft x-ray region, fast, suprathermal electrons in the laser driven plasma produce much harder x rays. This is shown in Figure 5.4 from Slivinsky.[11] Some of the many measurements of x-ray intensities are shown in Table 5.2 along with a comparison of the range of synchrotron radiation outputs.

SUMMARY

Laser produced plasmas now exist as usable light sources in the XUV and soft x-ray region. The applications of the sources follow directly from the specific properties of the sources, namely, that they are sources of radiation in the 10 eV to 10 keV region with very high peak intensities and low duty cycles giving average output fluxes, which can be comparable to synchrotron radiation sources. The outputs are unpolarized, with a full illumination sphere, from a point source and they are highly reproducible, in contrast to pulsed electric arc or discharge sources. They can be run in the presence of significant pressures of background gas and impurities and, at least for XUV sources, are moderately priced, compact, and easily portable.

In addition to being an intense source of XUV and soft x-ray radiation, laser produced plasmas have been shown to be as reproducible as the driving laser, provided the target illumination and observation geometry are kept fixed. Thus they are very promising for the role of transfer standards, although it will probably be necessary to use single transverse mode, smooth pulse lasers as the driving source. Efforts are now going on to study the use of such plasmas as intensity standards in the XUV.[17] The compactness and modest cost of XUV systems make these a natural candidate for such applications. In contrast to synchrotron radiation sources, laser plasmas would provide intensity standards for high intensity, short pulse radiation and could be used to calibrate detectors for these conditions without the large extrapolations needed with calibration from low peak intensity sources. The suitability as standards is particularly apparent for sources below ~300 eV where the laser plasma can produce a true continuum.

The continuum nature of the sources and their high reproducibility also make them excellent for spectroscopy, while the high intensity between 200 eV and 2 keV makes them well suited for materials application such as microlithography and the point source nature and toleration of ambient background gas make them well suited for x-ray microscopy. The high peak intensities are well suited for studying the interaction of intense bursts of ionizing radiation with matter, including efforts to produce highly nonequilibrium conditions suitable for x-ray laser operation.[5] The high reproducibility under easily prescribed conditions makes them excellent candidates for transfer standards in the XUV and soft x-ray regions.

Pulsed laser plasma light sources are still in need of extensive study to fully characterize their properties and optimize their outputs. However, sufficient work has been done since they were first observed 20 years ago to establish them as useful and sometimes essential sources for XUV and x-ray science.

Table 5.1 XUV Intensities and Fluxes from Laser-Produced Plasmas (Synchrotron parameters are qualitative for comparison.)

Ref	Laser Pulse Energy J	Measured Wavelength λ (nm)	Peak Spectral Intensity Phot. sec^{-1} MHz^{-1} mr^{-2}	Average Spectral Intensity (10 Hz rep. rate)	Peak Spectral Flux Phot. sec^{-1} MHz^{-1}	Average Spectral Flux (10 Hz rep. rate)
19	10	121.6	1.5×10^9	1.5×10^2	10^{16}	10^9
7	2	121.6	5×10^6	5×10^{-1}	3×10^{13}	3×10^6
17	2.2	121.6	10^7	1.0	6×10^{13}	6×10^6
16	0.8	100	3×10^7	3	2×10^{14}	2×10^7
16	0.8	15	1.510^7	1.5	10^{14}	10^7
16	0.8	6	7×10^5	7×10^{-2}	4×10^{12}	4×10^5
18	10	2.7	6×10^8	6×10^1	4×10^{15}	4×10^8
18	10	8	6×10^8	6×10^1	4×10^{15}	4×10^8
	Characteristic Synchrotron Radiation Parameters					
Bending Magnets			$10^5 - 10^8$	$10^3 - 10^4$	$5 \times 10^6 - 5 \times 10^9$	$5 \times 10^4 - 5 \times 10^5$
Wigglers			$10^6 - 10^9$	$10^4 - 10^5$	$5 \times 10^7 - 5 \times 10^{10}$	$5 \times 10^5 - 5 \times 10^6$
Undulators			$10^7 - 10^{11}$	$10^5 - 10^8$	$5 \times 10^8 - 5 \times 10^{12}$	$5 \times 10^6 - 5 \times 10^9$

Table 5.2 X-Ray Intensities and Fluxes from Laser-Produced Plasmas
(Synchrotron parameters are qualitative for comparison.)

Ref	Laser Intensity W cm^{-2}	Laser Pulse Duration ns	Laser Pulse Energy kJ	Measured Output Photon Energy kev	Peak Spectral Intensity Phot. sec^{-1} 10%BW mr^{-2}	Peak Spectral Flux Phot. sec^{-1} 10% BW
11	3×10^{14}	2.2	4.1	40	5×10^{13}	3×10^{20}
11	3×10^{14}	2.2	4.1	160	5×10^{12}	3×10^{19}
11	3×10^{14}	2.2	4.1	350	5×10^{10}	3×10^{17}
10	3×10^{15}	0.7	.6	1.8 - 3.6	7×10^{16}	4×10^{23}
13	5×10^{14}	.5	.04(.35μ)	2.7	2×10^{17}	10^{24}
15	4×10^{13}	8	.028	1	7×10^{16}	4×10^{23}
Synchrotron Radiation Sources						
Bending Magnets				<100	$10^{14} - 10^{15}$	$5 \times 10^{15} - 5 \times 10^{16}$
Wigglers				<200	$10^{15} - 10^{16}$	$5 \times 10^{16} - 5 \times 10^{17}$
Undulators (projected)				<10	$10^{16} - 10^{19}$	$5 \times 10^{17} - 5 \times 10^{20}$

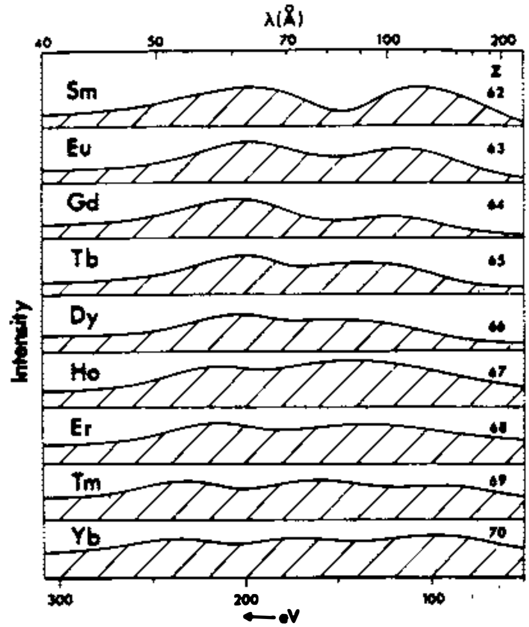

FIGURE 5.1. Qualitative representation of continuum intensity distribution from laser produced plasmas using rare earth targets[6].

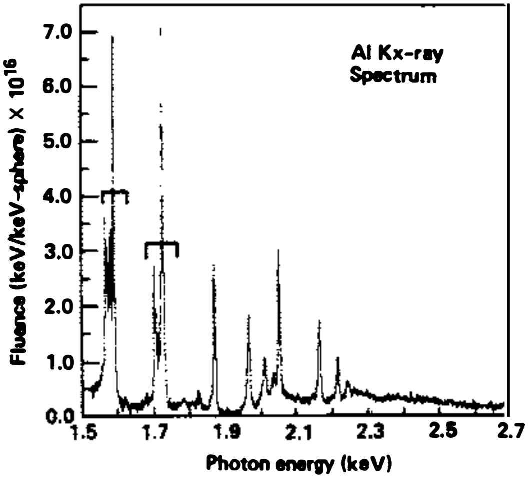

FIGURE 5.2. X-ray intensity distribution from Al target[10].

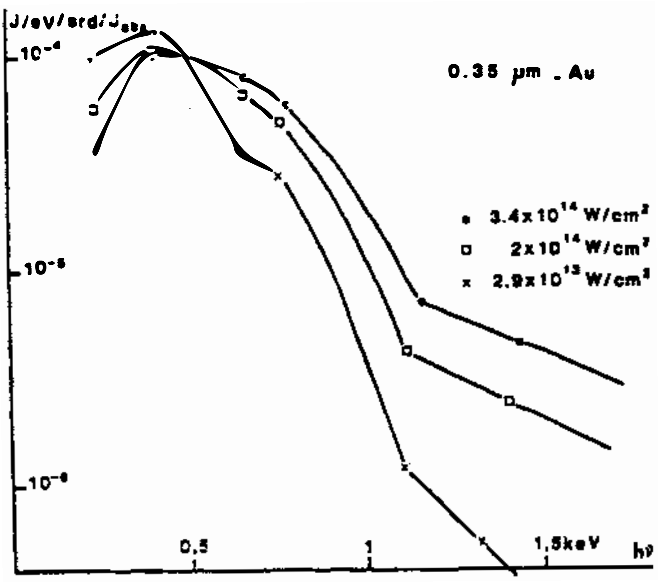

FIGURE 5.3. Intensity distribution for different incident laser fluxes using Au target and .35 μm irradiation[16].

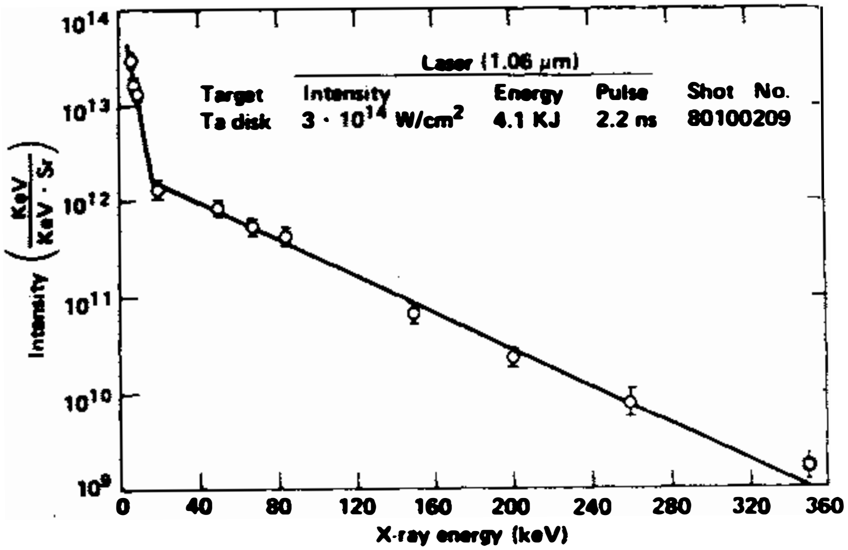

FIGURE 5.4. Suprathermal x-ray spectrum from a Ta target[11].

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6. FREE ELECTRON LASERS FOR THE XUV SPECTRAL REGION*

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1. Remarkable experimental progress has been made on the free electron laser (FEL) during the last two years. FEL oscillators and amplifiers have been operated, at wavelengths varying from the centimeter to the visible and near UV and at power level up to about one hundred MW peak power, in many laboratories: MSNW, TRW-Stanford, LASL, LBL-LLNL, MIT, NRL, Columbia-NRL, U.C.-Santa Barbara and Orsay. These FELs thus join the first FEL oscillator built by Madey and collaborators in 1978.[1-6]

The theory of FELs has at the same time reached a high level of completeness and is in good agreement with the experimental results.

Because of this experimental and theoretical progress, we have now a good understanding of the physics and technology of FELs, and we have also the capability

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of designing systems operating in new wavelength regions, like the XUV spectral region.

The possibility of building a FEL operating at wavelengths shorter than 1000Å is a result of the progress made in producing high density relativistic electron beams using electron storage rings. Storage rings specially designed for FEL applications and capable of accommodating undulator magnets 5 to 15 m long, should offer the possibility of producing coherent radiation down to a few hundred angstroms with average power of the order of watts and peak power up to hundreds of megawatts. One such ring is being built at Stanford University,[7] and similar rings are being studied also in other laboratories.[8,9]

2. In a FEL a relativistic electron beam and an electromagnetic wave traverse an undulator. The coupling of the wave and the transverse electron beam current, induced by the undulator, can produce an energy transfer between the beam kinetic energy and the radiation field energy, if a synchronism condition is satisfied.[10] This condition relates the radiation field wavelength λ, the undulator period λ_u, field B_u, the parameter $K = eB_u\lambda_u/2\pi mc^2$, and the beam energy γ measured in rest energy units mc^2:

$$\lambda = (\lambda_u/2\lambda^2)(1+K^2) \qquad (1)$$

(Notice that this wavelength is also the wavelength at which the spontaneous radiation from an electron traversing an undulator is emitted.)

An important property of the FEL is that the energy transfer between the beam and the radiation can be enhanced by a collective instability producing an exponential growth of the radiation[11]. When this instability becomes important the FEL is said to operate in the high gain regime. The existence of this regime is very important for the FEL operation in the XUV region where we do not have optical components with high reflectivity and small absorption.[12]

Three modes of operation of a FEL have been considered. In the first mode, Self Amplified Spontaneous Emission (SASE), the initial spontaneous radiation emitted by the electrons, is amplified; this system does not require any optical component but needs a high density electron beam and a rather long undulator.[8,11]

The second mode is the FEL oscillator. An optical cavity is used to reflect back and forth the radiation for further amplification by another electron bunch. This system requires a smaller electron beam density and a shorter undulator but needs mirrors for the cavity; at wavelengths smaller than 1000Å these mirrors have still to be developed and their reflectivity is expected to be on order of 50 percent.[12]. In the third mode, or Transverse Optical Klystron,[13] an external laser beam at the spontaneous radiation wavelength is used to modulate the beam energy and longitudinal density distribution, thus leading to the emission of coherent radiation at the higher harmonics of the input laser. Of the three modes this is the one requiring the least stringent electron beam parameters. It does not need optical elements; on the other hand it requires an undulator with rather strict magnetic field tolerances and produces the smallest coherent radiation power.

3. In all these modes the FEL can be characterized by one parameter, N*, the FEL e-folding length, measured in number of undulator periods[11]

$$N^* = 2/(\pi^{1/2} 3^{3/4} K\lambda_u \Omega_\rho / c)^{2/3} \qquad (2)$$

where Ω_ρ is the electron beam plasma frequency, defined in terms of the electron density n_o, and energy γ, by

$$\Omega_\rho = (4\pi r_e c^2 n_o/\gamma^3)^{1/2} \qquad (3)$$

r_e being the classical electron radius.

For an oscillator to operate at short wavelength, where the optical cavity losses can be on the order of 100 percent per round trip, one needs a number, N_u, of undulator periods on the order of N*, i.e., a ratio of $N_u/N^* \sim 1$.

In the case of SASE[11] the value of the ratio N_u/N^* must be on the order of 10.

In both cases the energy transfer from the beam to the radiation field is on the order of $1/(4\pi N^*)$, while in the TOK case the transfer from the input laser to the harmonics is rather small.

The expression (2) for the FEL growth rate applies only if two other conditions on the electron beam are satisfied. One is a condition on the beam energy spread, which must be less than $1/(4\pi N^*)$; the second is a condition on the beam emittance, which must be smaller than the radiation wavelength. If these conditions are not satisfied the radiation growth rate decreases, and the output laser power becomes smaller.[8]

For wavelengths in the millimeter region and electron energy of a few MeV, the value of N* can be on the order of 10, while in the VUV region and electron energies of several hundreds of MeV, N* can be on the order of 100 to 1000, and one can expect an energy transfer from the beam to the radiation on the order of a few parts in a thousand.

4. In the wavelength region below 1000Å, the best accelerator to produce high density electron beams is at the moment an electron storage ring. Existing storage rings, like the VUV of the National Synchrotron Light Source at Brookhaven, can provide an average emittance on the order of 10^{-8} mrad, an energy spread of about 10^{-3}, and a peak current of 60Å at an energy of 750 MeV. A ring like this, with straight sections capable of accommodating undulators 5 to 6 m long, would allow us to produce coherent radiation in the 1000Å region.

We believe that it is now possible to design a storage ring with an energy of 700 to 1000 MeV, an emittance smaller by an order of magnitude, same energy spread, and peak currents in the range of 100 to 200Å. Such a ring would allow us to produce radiation in the wavelength range of 100 to 500Å using undulators about 10 m long.[7,8,9] Using this ring, the peak radiation power that one can obtain in the SASE mode is on the order of 10^{-3} times the beam peak power, or 100 MW. This pulse would have a duration of about 100 ps and a repetition rate of 10 Hz, for an average radiation power of 0.1 W.

With the same system operating in the oscillator mode, one can obtain an average output power of the order of 1 W, pulse duration of about 100 ps, a repetition rate, determined by the ring revolution time, on the order of a few MHz, and a peak power of about 10 KW. For this oscillator it is also possible, by modulating the system gain, to reduce the repetition rate and increase the peak power.

For the TOK mode one can expect conversion efficiencies on the order of 10^{-6} around the tenth harmonics, so that starting with a 100-MW peak power laser at 2000Å, one should be able to produce about 100 W at around 200Å.

In all of these cases the angular distribution of the radiation is determined by the electron beam radius, a, and the radiation wavelength; the characteristic angle is on the order of λ/a, i.e., of a few tenths of milliradians. The line width is on the order of the wavelength divided by the electron bunch length, i.e., 10^{-6}, for the oscillator and the TOK mode. For the SASE mode it depends on the detail of the system and is intermediate between the oscillator limit and the inverse of the number of periods in the undulator, i.e., between 10^{-6} and 10^{-3}.

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FINAL NOTE

Reproductions of presentation Vu-Graphs by Drs. Attwood, McIlrath, Pelligrini, Rhodes, and Winick are available from the Board on Physics and Astronomy upon request.