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Atomic Physics Research with Second and Third Generation Synchrotron Light Sources*

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ABSTRACT

This contribution to these proceedings is intended to provide an introduction and overview for other contributions on atomic (and related) physics research at existing and planned synchrotron light sources. The emphasis will be on research accomplishments and future opportunities, but a comparison will be given of operating characteristics for first, second, and third generation machines. First generation light sources were built to do research with the primary electron and positron beams, rather than with the synchrotron radiation itself. Second generation machines were specifically designed to be dedicated synchrotron-radiation facilities, with an emphasis on the use of bending-magnet radiation. The new third generation light sources are being designed to optimize radiation from insertion devices, such as undulators and wigglers. Each generation of synchrotron light source offers useful capabilities for forefront research in atomic physics and many other disciplines.

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1. Background and Introduction

Atomic Physics and related phenomena underlie all of synchrotron radiation (SR) research. In the same sense that the development of atomic models in the early years of this century formed the cornerstone for the birth of quantum mechanics, the first atomic physics experiments with SR in the 1960's and 1970's provided the foundation for the genesis of all modern synchrotron-radiation research.

The pioneering atomic-physics experiment by Madden and Codling[1] was the first measurement at a permanent synchrotron radiation facility (SURF at the then National Bureau of Standards in Gaithersburg, MD). The experiment was a total photoabsorption study with UV synchrotron radiation. Absorption measurements monitor the change in photon flux downstream of a gas or vapor target as a function of incident photon energy. Total photoabsorption cross sections and resonant excitation energies can be measured with low-intensity radiation sources (10^5 photons/sec) and high target cell pressures (1 to 100 Torr). However, more complex experiments (e.g. fluorescence, ion, or electron spectroscopy), which provide information on subshell excitation and a deeper understanding of the photoionization process, require higher photon fluxes (at least 10^9 photons/sec) and lower target pressures (typically 10^{-4} Torr). Hence the need for improved synchrotron radiation facilities.

Spectroscopy experiments with SR were begun in the 1970's at first generation synchrotron light sources[2,3]. Such facilities were designed and built for high-energy physics experiments which used the primary electron or positron beams. The facilities were initially available for SR research only in a parasitic mode, but many of them eventually became partly or fully dedicated as synchrotron light sources. In the 1980's second-generation machines were built to be specifically dedicated to SR research. Most third generation machines are just now being designed and built, but SuperACO at Orsay is already operational. Wuilleumier and Crasemann have given extensive reviews[4,5] of the early SR measurements on atoms. A brief overview of synchrotron light sources, generic

beam-line design considerations, and SR research in atomic physics and related disciplines will be given here.

2. Synchrotron Radiation Facilities

Overviews of facilities which are used for synchrotron-radiation research have been given periodically by H. Winick[6] of the Stanford Synchrotron Radiation Laboratory (SSRL) and others[7]. The listings are usually grouped geographically and they give the location, laboratory and/or ring name, the stored electron- or positron beam energy, and an indication of project status or operational condition. Tables I, II, and III reorder recent tabulations[6,7] first by generation of light source and then in increasing order of stored beam energy.

The usual chronological distinction for generation of light source is that most second-generation machines were built and became operational in the 1980's, while first-generation machines existed earlier and the new third-generation machines are just now being designed and built. However, the operational distinction is more important and it is on that basis that the tables are arranged. Most first generation machines (Table I) were built to utilize the extracted electron or positron beams and SR research was parasitic. They are often only partly dedicated to SR research, even today. The second- and third-generation machines (Tables II and III) are purposely designed to be dedicated synchrotron light sources. Although some first-generation machines have become partly or fully dedicated to SR research and their operational characteristics have been improved, the second- and third-generation facilities almost always offer better beam stability, higher photon fluxes, and generally superior research capabilities.

Almost all SR light sources are synchrotron storage rings. Stored electrons or positrons travel in a closed loop within evacuated chambers. The orbit is not strictly circular, but instead is a series of arcs or bends connected by straight sections. Synchrotron radiation is produced either in the dipole bending magnets or in special insertion devices which are periodic arrays of magnets "inserted" in a straight section. Insertion devices are also called

wigglers and undulators because the beam is caused to "wiggle" or "undulate" when passing through them. The primary difference between second- and third-generation SR facilities is the emphasis on radiation from bending-magnets versus insertion-devices, respectively. However, all third generation facilities have some bending magnet ports, while most second-generation light sources have one or more insertion devices.

It is beyond the scope of this work to discuss either the details of synchrotron light source design and operation or the relative merits of bending-magnet versus insertion device radiation. The interested reader is referred to a recent comprehensive introduction and overview of SR facilities and research opportunities by Margaritondo[8], a discussion of the challenges of third-generation light sources by Jackson[7], and recent status reports on progress in design and construction of the new light sources to be found elsewhere in these proceedings[9,10].

2. Synchrotron Radiation Beam-Line Considerations

Beam lines for atomic-physics research at synchrotron radiation facilities must be carefully designed. Unlike materials-science, condensed-matter-physics, and applied SR studies which employ solid samples, atomic-physics research uses isolated atomic or molecular targets in the form of a gas, a vapor, or a beam of ions. These tenuous targets result in fewer photoionization events and consequently lower counting rates than solid-sample studies. Therefore, it is highly desireable to maximize the available photon flux delivered to most atomic physics experiments.

Fig. 1 illustrates the relevant parameters[11] that determine the photon flux, N_{out} ($h\nu$), available for an experiment. The governing equation is:

$$N_{out}(h\nu) = N(h\nu)\, \theta_x\, T_B\, T_M\, (\alpha_x / \epsilon_{1x})\, (\alpha_y / \epsilon_{1y}), \qquad (1)$$

where θ_x is the horizontal divergence angle of emitted radiation from the bending magnet or insertion device of interest, and the other parameters are as defined in Fig. 1.

Eq. (1) dictates the steps necessary to maximize the photon flux for SR experiments:

1. Design Light Source for maximum photon flux and minimum emittances (horizontal and vertical).
2. Design both beam line and monochromator to accept the largest possible solid angles.
3. Match acceptances of monochromator and beam line to the emittance of the source.
4. Maximize transmission of beam line and monochromator.

Put another way, if maximum photon flux is desired, the beam line design goals should be to maximize the source photon flux, θ_x, the transmission of beam line and monochromator, and the monochromator acceptance solid angles, and to minimize the beam line and source emittances. Some specific examples of how these principles are applied to actual experimental beam lines are given elsewhere[12-27].

3. Studies of Atomic Physics and Related Phenomena

There have been several workshops on atomic physics at second- and third-generation SR facilities. The first was held in 1980 at Brookhaven National Laboratory (BNL)[12]. Considerable interest and excitement were expressed for the potential impact on Atomic, Molecular, and Optical (AMO) physics research promised by the new (second-generation) National Synchrotron Light Source (NSLS), which was then under construction. There have been at least two similar workshops on atomic physics for third-generation facilities. These at Grenoble[14] in 1988 for the European Synchrotron Radiation Facility (ESRF) and at Argonne[15] in 1990 for the Advanced Photon Source (APS).

Although there has been considerable activity in AMO research with SR in the past decade, many of the conclusions of the NSLS workshop[12] in 1980 are still true today. For example:

1. The AMO physics community seems to be more interested in soft-x and VUV photons, than in hard x rays.

2. There have been very few measurements on the photoionization of ions, particularly for inner-shells.

3. The next generation of new light sources will undoubtedly enhance experimental capabilities in current research programs and foster the development of new research endeavors.

The session on synchrotron radiation research, for which this contribution serves as an introduction, is intended to address recent progress in both ongoing research programs at existing facilities and plans for new endeavors at future light sources. Research in AMO physics is the focus, but related and interdisciplinary fields are also addressed.

The topics covered are:

1. Nuclear Resonant Bragg Scattering[15].
2. Vibrational Excitation Effects on Core Exciton Spectra[16].
3. Photoionization of Ions and Laser-Excited Atoms at Super ACO[17].
4. Anisotropy of Polarized X-Ray Emission from Free Molecules[18].
5. K-Shell Photoionization of Argon Ions Using Synchrotron Radiation and a Penning Ion Trap[19].
6. Photoion Auger-Electron Coincidence Measurements Near Threshold[20].
7. Molecular Studies Using Imaging Time-of-Flight Techniques[21].
8. The Advanced Light Source at LBL[9].
9. Atomic, Molecular, and Optical Physics with X Rays[22].
10. Atomic Physics Experiments Using VUV and Soft X Radiation[23].
11. Atomic Physics at the Advanced Photon Source[24].

Related presentations also to be found in these proceedings include:

A. Collision Measurements Using Cold Ions Produced by Synchrotron Radiation[25].

B. Photoionization of Excited Atoms Using Synchrotron Radiation[26].

C. Inner-Shell Photoionization Studies Using Ion Beams and Synchrotron Radiation[27].

No attempt will be made here to summarize the content of these presentations, because many of them are overviews themselves of research at both existing and planned facilities[9,17,22-24]. The first two listed above[15,16] are not traditional fields of atomic physics research, but concern atomic-physics phenomena. The others primarily address AMO topics and chronicle both very recent activity[15-26] and planned research[9,17,21-24,27]. Most of the presentations emphasize research accomplishments or potential opportunities at one particular facility: the ALS[9,22-23], the APS[24], the NSLS UV ring[16,26], the NSLS x-ray ring[15,18,19-21,25,27], and Super ACO[17].

4. Conclusions

Synchrotron radiation research in Atomic, Molecular, and Optical and Optical physics is an important field of both fundamental and applied research. Progress has been strongly coupled to the development of improved light source facilities, because the study of isolated atomic and molecular systems mandates the use of tenuous gas-phase and ion-beam targets. This usually results in the desire for maximum experimental photon flux. Careful consideration must be given to the optimum design of not just the experimental apparatus at the end of SR beam lines, but to the entire combination of light source, beam line, monochromator, and interaction chamber.

Each generation of SR facility provides numerous opportunities for AMO research, but the second- and third-generation light sources offer distinct advantages over the first. Namely, the operation of the newer facilities is dedicated to SR research; operating characteristics (eg. beam stability, source photon flux, and photon energy range) are improved and extended; and user support services are improved to provide a more productive research environment.

Other contributions to these proceedings collectively provide an excellent overview and summary of recent achievements, current plans, and future possibilities. The future of SR research in AMO physics is bright.

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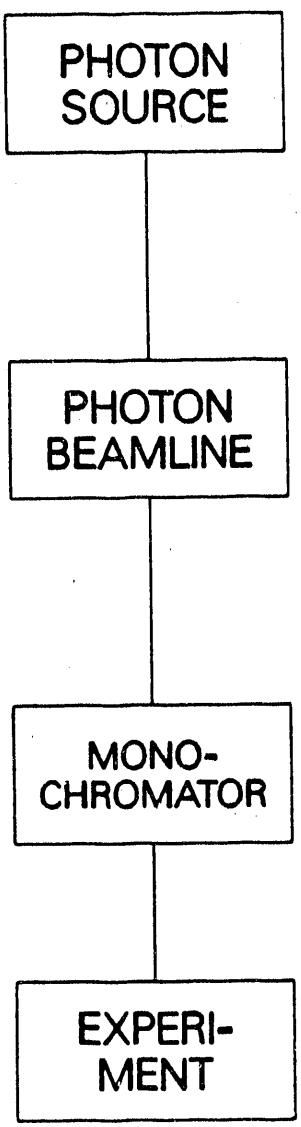
Figure Captions

Figure 1. A graphical representation of the relevant parameters that determine the photon flux available for an experiment with synchrotron radiation (adapted from [11]). The goal in most atomic physics research is to deliver the maximum photon flux available to the experiment. This requires minimizing the emittances and maximizing all other parameters.

GENERIC BEAM LINE CHARACTERISTICS FOR SYNCHROTRON RADIATION EXPERIMENTS



$N(h\nu)$	Source Photon Flux
ε_{0x}	Horizontal Source Emittance
ε_{0y}	Vertical Source Emittance
T_B	Beamline Transmission Coefficient
ε_{1x}	Horizontal Beamline Emittance
ε_{1y}	Vertical Beamline Emittance
T_M	Mon. Transmission Coefficient
α_x	Mon. Horizontal Acceptance
α_y	Mon. Vertical Acceptance
$N_{out}(h\nu)$	Photon Flux for Experiment

Figure 1

Table 1

First Generation Synchrotron Light Sources.[6] Most of these early facilities were built to do research with the primary electron or positron beams. Synchrotron radiation research was parasitic. Today, all have become at least partly dedicated as synchrotron light sources.

Storage Ring (Lab)	Energy (GeV)	Location	Project Phase
SURF I (NIST)	0.18	Gaithersburg, USA	Dedicated
EUTERPE (TUE)	0.4	Eindhoven, THE NETHERLANDS	Partly Ded. Under Const.
ACO (LURE)	0.54	Orsay, FRANCE	Defunct
ASTRID (ISA)	0.6	Aarhus, DENMARK	Partly Ded.
ADONE (LNF)	1.5	Frascati, ITALY	Dedicated
DCI (LURE)	1.8	Orsay, FRANCE	Partly Ded.
VEPP-3 (INP)	2.2	Novosibirsk, USSR	Partly Ded.
BEPC (IHEP)	2.2 - 2.8	Beijing, CHINA	Partly Ded.
SPEAR (SSRL)	3.0 - 3.5	Stanford, USA	Partly Ded.
ELSA (Bonn Univ.)	3.5	Bonn, GERMANY	Partly Ded.
DORIS II (HASYLAB)	3.5 - 5.5	Hamburg, GERMANY	Partly Ded.
VEPP-4 (INP)	5.0 - 7.0	Novosibirsk, USSR	Partly Ded.
CESR (CHESS)	5.5 - 8.0	Ithaca, USA	Partly Ded.
Acc. Ring (KEK)	6.0 - 8.0	Tsukuba, JAPAN	Partly Ded.
Tristan (KEK)	25 - 30	Tsubuka, JAPAN	Partly Ded.

Table 2

Second Generation Synchrotron Light Sources.[6] This is the first generation of machines built to be dedicated synchrotron radiation facilities. The use of bending magnet ports is emphasized although some straight sections have insertion devices (e.g. undulators and wigglers).

Storage Ring (Lab)	Energy (GeV)	Location	Project Phase
N-100 (KPI)	0.10	Kharkov, USSR	Operating
SURF II (NIST)	0.28	Gaithersburg, USA	Operating
SOR-Ring (ISSP)	0.38	Tokyo, JAPAN	Operating
Siberia I (KI)	0.45	Moscow, USSR	Operating
MAX (Univ. Lund)	0.55	Lund, SWEDEN	Operating
TERAS (ETL)	0.6	Tsukuba, JAPAN	Operating
NSLS UV (BNL)	0.75	Upton, USA	Operating
UVSOR (IMS)	0.75	Okasaki, JAPAN	Operating
BESSY	0.8	Berlin, GERMANY	Operating
Aladdin (SRC)	0.8 - 1.0	Stoughton, USA	Operating
CAMD (LSU)	1.2	Baton Rouge, USA	Proposed
SOR (KU)	1.5	Kyushu, JAPAN	Operating
DELTA (DU)	1.5	Dortmund, GERMANY	Operating
NSLS x-ray (BNL)	2.5	Upton, USA	Operating
Photon Fac. (KEK)	2.5	Tsukuba, JAPAN	Operating

Table 3

Third Generation Synchrotron Light Sources.[6,7] This is the newest generation of dedicated synchrotron radiation facilities. The use of insertion devices (e.g. undulators and wigglers) is emphasized, but bending-magnet ports will also be available.

Light Source	Energy (GeV)	Location	Project Phase
HESRYL	0.8	Hefei, CHINA	Commissioning
Super-ACO	0.8	Orsay, FRANCE	Operating
ALS	1.0 - 1.9	Berkeley, USA	Construction
SRRC	1.3	Hsinchu, ROC	Construction
INDUS II	1.4	Indore, INDIA	Authorized
MAX II	1.5	Lund, SWEDEN	Design
BESSY II	1.5 - 2.0	Berlin, GERMANY	Design
ELETTRA	1.5 - 2.0	Trieste, ITALY	Construction
LNLS	2.0	Campinas, BRAZIL	Authorized
PLS	2.0	Pohang, KOREA	Authorized
SIBERIA II	2.5	Moscow, USSR	Construction
ESRF	6.0	Grenoble, FRANCE	Construction
APS	7.0	Argonne, USA	Construction
STA	8.0	Kansai, JAPAN	Design
DAPS	???	Daresbury, UK	Design

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