## Title
Pocket Diary for X-Ray and Euv Scientists 2003

## Permalink
https://escholarship.org/uc/item/6xk922r3

## Author
Lawrence Berkeley National Laboratory

## Publication Date
2002-09-01

# POCKET DIARY

# FOR

# X-RAY AND EU

# SCIENTISTS

# 2003

**Center for X-Ray Optic**

**Lawrence Berkeley National La**
**Berkeley, CA 94720, US**

# POCKET DIARY

# FOR

# X-RAY AND EUV

# SCIENTISTS

# 2003

Center for X-Ray Optics
Lawrence Berkeley National Laboratory
Berkeley, CA 94720, USA

http://www-cxro.lbl.gov/

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, and the Extreme Ultraviolet Lithography Limited Liability Corporation under CRADA Contract No. BG97217.

LBNL/PUB-847 (Rev. 9/02)

Labor Day (US Canada) 245

3 Tue

246

4 Wed

247

5 Thu

MEDSI 2002, Argonne, IL 248

6 Fri

249

7 Sat

Independence Day (Brazil) 250

8 Sun

251

FEL 2002, Argonne, IL

252

10 Tue

Spring-8 Sympos., Hyogo, Japan

253

11 Wed

SRS Users, Daresbury, UK

254

12 Thu

255

13 Fri

256

14 Sat

257

15 Sun

258

ANKA Users, Karlsruhe, Germany

Independence Day (Mexico);Yom Kipper (begins sunset previous day) 259

17 Tue

260

18 Wed

261

19 Thu

MAX-lab Users, Lund, Sweden 262

20 Fri

263

21 Sat

264

22 Sun

M. Faraday—1791 265

# SEPTEMBER 23 Mon
## 2002 Week 39

OSA Ann., Orlando, FL 266

## 24 Tue

267

## 25 Wed

SAS-2000, Venice
SLS Users, Switzerland 268

## 26 Thu

269

## 27 Fri

270

## 28 Sat

Confucius' Birthday 271

## 29 Sun

272

SEPTEMBER 30 Mon
2002 Week 40

OSA/ILS-XVIII, Orlando, FL 273

OCTOBER 1 Tue
2002

Founding Day (People's Republic of China) 274

2 Wed

275

3 Thu

National Foundation Day (Republic of Korea)
Tag der deutchen Einheit (Germany) 276

4 Fri

277

5 Sat

Republic Day (Portugal) 278

6 Sun

279

7 Mon

SSRL Users, Stanford

N. Bohr—1885

280

8 Tue

281

9 Wed

ALS Users, Berkeley

282

10 Thu

283

11 Fri

284

12 Sat

Dia de la Hispanidad (Spain)

285

13 Sun

286

Columbus Day (US), Thanksgiving Day (Canada) 287

15 Tue

288

16 Wed

289

17 Thu

290

18 Fri

291

19 Sat

292

20 Sun

293

294

22 Tue

295

23 Wed

Day of the Hungarian Republic 296

24 Thu

Sematech EUV, Dallas, TX 297

25 Fri

298

26 Sat

National Holiday (Austria) 299

27 Sun

Return to Standard Time
(set clock back 1 h at 0200 Mon. Morning) 300

Elettra Users, Trieste

301

29 Tue

302

30 Wed

303

31 Thu

Hallowe'en

SRRC Users, Hsinshu, Taiwan

304

NOVEMBER 2002 1 Fri

305

2 Sat

306

3 Sun

307

4 Mon
Week 45

308

5 Tue

Guy Fawkes Day (UK)

309

6 Wed

First day of Ramadan (begins sunset previous day)

310

7 Thu

311

8 Fri

312

9 Sat

313

10 Sun

314

11 Mon

APS Plasma, Orlando, FL

Armistice Day; National Independence Day (Poland)

315

12 Tue

316

13 Wed

317

14 Thu

318

15 Fri

Can. Light Source Users, Saskatoon

Republic Day (Brazil)

319

16 Sat

320

17 Sun

321

322

19 Tue

323

20 Wed

324

21 Thu

325

22 Fri

326

23 Sat

328

24 Sun

329

26 Tue

330

27 Wed

331

28 Thu

Thanksgiving Day (US) 332

29 Fri

333

30 Sat

Hanukah (begins sunset previous day) 334

DECEMBER 1 Sun
2002

335

2 Mon
Week 49

APS Plasma Phys., Orlando, FL

336

3 Tue

337

4 Wed

338

5 Thu

BESSY Users, Berlin

W. Heisenberg—1901

Last day of Ramadan (begins sunset previous day)

339

6 Fri

Independence Day (Finland)

340

7 Sat

XRMS 2002, Dresden, Germany

341

8 Sun

342

343

10 Tue

344

11 Wed

345

12 Thu

346

13 Fri

347

14 Sat

348

15 Sun

H. Becquerel—1852

350

17 Tue

351

18 Wed

J.J. Thomson—1856

352

19 Thu

A. Michelson—1852

353

20 Fri

354

21 Sat

355

22 Sun

356

Emperor's Birthday (Japan) 357

24 Tue

358

25 Wed

Christmas

I. Newton—1642 359

26 Thu

Boxing Day (UK, Canada, Australia) 360

27 Fri

J. Kepler—1571 361

28 Sat

362

29 Sun

363

DECEMBER 30 Mon
2002 Week 1

364

31 Tue

LG-3

365

JANUARY 1 Wed
2003

New Year's Day

1

2 Thu

Holiday (Scotland)

2

3 Fri

3

4 Sat

4

5 Sun

5

6

7 Tue

7

8 Wed

8

9 Thu

UVSOR Users, Himeji, Japan

9

10 Fri

10

11 Sat

11

12 Sun

12

13

14 Tue

14

15 Wed

15

16 Thu

16

17 Fri

17

18 Sat

18

19 Sun

Martin Luther King Day (US) 20

21 Tue

21

22 Wed

22

23 Thu

23

24 Fri

24

25 Sat

25

26 Sun

Australia Day
Republic Day (India) 26

27

28 Tue

28

29 Wed

29

30 Thu

30

31 Fri

HASYLAB Users, Hamburg

31

FEBRUARY 1 Sat
2003

Chinese New Year (Year 4701, Ram)

32

2 Sun

33

3 Mon
Week 6

34

4 Tue

35

5 Wed

36

6Thu

New Zealand Day

37

7 Fri

38

8 Sat

39

9 Sun

40

41

11 Tue

42

12 Wed

Lincoln's Birthday (US)
ESRF Users, Grenoble 43

13 Thu

44

14 Fri

Galileo Galilei—1564
Valentine's Day 45

15 Sat

46

16 Sun

47

Presidents Day (US)

48

18 Tue

49

19 Wed

50

20 Thu

51

21 Fri

52

22 Sat

53

23 Sun

54

FEBRUARY 24 Mon
2003 Week 9

55

25 Tue

56

26 Wed

57

27 Thu

58

28 Fri

59

MARCH 1 Sat
2003

60

2 Sun

61

Independence Mvmt. Day (Rep. of Korea) 62

4 Tue

63

5 Wed

Islamic New Year 1424 (begins sunset previous day) 64

6 Thu

65

7 Fri

66

8 Sat

International Womens Day 67

9 Sun

68

69

11 Tue

70

12 Wed

71

13 Thu

72

14 Fri

A. Einstein—1879

73

15 Sat

National Holiday (Hungary)

74

16 Sun

75

St. Patrick's Day 76

18 Tue

77

19 Wed

78

20 Thu

79

21 Fri

80

22 Sat

R. Millikan—1868 81

23 Sun

Pakistan Day 82

83

25 Tue

84

26 Wed

85

27 Thu

86

28 Fri

87

29 Sat

88

30 Sun

W. Europe, Russia: Daylight Saving Time begins
(set clock ahead 1 h at 0200 Mon. Morning)

MARCH 31 Mon
2003 Week 14

90

APRIL 1 Tue
2003

91

2 Wed

92

3 Thu

93

4 Fri

94

5 Sat

95

6 Sun

Daylight Saving Time begins (US)
(set clock ahead 1 h at 0200 Mon. Morning) 96

97

8 Tue

98

9 Wed

99

10 Thu

100

11 Fri

101

12 Sat

102

13 Sun

103

104

15 Tue

105

16 Wed

Queen's Birthday (Denmark) 106

17 Thu

Passover (begins sunset previous day) 107

18 Fri

Good Friday 108

19 Sat

109

20 Sun

Easter 110

MRS, San Francisco, CA

111

22 Tue

Earth Day

112

23 Wed

M.Planck—1858

113

24 Thu

114

25 Fri

CAMD Users, Baton Rouge, LA
Holiday (Italy)
W. Pauli—1900

115

26 Sat

116

27 Sun

Orthodox Easter

117

APRIL 28 Mon
2003 Week 18

APS Users, Argonne, IL 118

29 Tue

119

30 Wed

Queen's Birthday (Netherlands)
K. Gauss—1777 120

MAY 1 Thu
2003

May Day (Labor Day) 121

2 Fri

122

3 Sat

Constitution Day (Japan; Poland) 123

4 Sun

124

DIPAC 2003, Mainz, Germany
Cino de Mayo (Mexico)

125
6 Tue

126
7 Wed

127
8 Thu

128
9 Fri

129
10 Sat

130
11 Sun

Mothers Day
R. Feynman—1918

131

132

13 Tue

133

14 Wed

134

15 Thu

P. Curie—1859

135

16 Fri

136

17 Sat

Constitution Day (Norway)

137

18 Sun

138

Victoria Day (Canada)

NSLS Users, Upton, NY

139

20 Tue

140

21 Wed

DMOP 2003, Boulder, CO

141

22 Thu

142

23 Fri

143

24 Sat

144

25 Sun

145

MAY 26 Mon
2003 Week 22

Memorial Day (US)
Holiday (England, Wales)

146

27 Tue

147

28 Wed

148

29 Thu

149

30 Fri

150

31 Sat

151

JUNE 2003 1 Sun

152

Constitution Day (Italy) 153

3 Tue

154

4 Wed

155

5 Thu

Constitution Day (Denmark) 156

6 Fri

Memorial Day (Rep. of Korea) 157

7 Sat

158

8 Sun

159

160

10 Tue

161

11 Wed

162

12 Thu

Independence Day (Russia) 163

13 Fri

J. Maxwell—1831 164

14 Sat

Queen's Birthday (UK, observed)

C. Coulomb—1736 165

15 Sun

166

ICESS-9, Uppsala, Sweden

167

17 Tue

168

18 Wed

169

19 Thu

170

20 Fri

171

21 Sat

172

22 Sun

173

XAFS12, Malmö, Sweden

174

24 Tue

175

25 Wed

176

26 Thu

177

27 Fri

178

28 Sat

179

29 Sun

180

JUNE 30 Mon
2003 Week 27

181

JULY 1 Tue
2003

Canada Day

182

2 Wed

183

3 Thu

184

4 Fri

Independence Day (US)

185

5 Sat

186

6 Sun

187

188

8 Tue

189

9 Wed

190

10 Thu

191

11 Fri

192

12 Sat

193

13 Sun

194

Bastille Day (France)

Gordon Conf. X-Ray Phys., Bristol, RI

195

15 Tue

196

16 Wed

197

17 Thu

Republic Day (Rep. of Korea)

198

18 Fri

H. Lorentz—1853

199

19 Sat

200

20 Sun

201

National Day (Belgium) 202

22 Tue

203

23 Wed

ICPEAC 2003, Stockholm 204

24 Thu

205

25 Fri

206

26 Sat

Am.Crystall.Assn.Mtg., Cincinnati, OH 207

27 Sun

208

P. Cherenkov—1904

209

29 Tue

210

30 Wed

211

31 Thu

LG-3

212

AUGUST 2003 1 Fri

Confederation Day (Switzerland)

213

2 Sat

214

3 Sun

215

Holiday (Canada, Scotland)

216

5 Tue

217

6 Wed

218

7 Thu

219

8 Fri

P. Dirac—1902

E.O. Lawrence—1901

220

9 Sat

221

10 Sun

222

11 Mon

223

12 Tue

224

13 Wed

225

14 Thu

Independence Day (Pakistan)

226

15 Fri

Independence Day (India, Rep. of Korea)

227

16 Sat

228

17 Sun

229

230

19 Tue

231

20 Wed

Holiday (Hungary) 232

21 Thu

233

22 Fri

234

23 Sat

235

24 Sun

236

A

B

C

D

EF

G

H I

J K

L

M

NO

P

Q R

S

WXYZ

SRI 2003, San Francisco

ECM-21, Durban, So. Africa

237

26 Tue

238

27 Wed

239

28 Thu

240

29 Fri

241

30 Sat

E. Rutherford—1871

242

31 Sun

H. Helmholtz—1821

243

Labor Day (US, Canada) 244

2 Tue

245

3 Wed

246

4 Thu

247

5 Fri

248

6 Sat

249

7 Sun

Independence Day (Brazil) 250

SEPTEMBER 8 Mon
2003 Week 37

251

9 Tue

252

10 Wed

253

11 Thu

254

12 Fri

255

13 Sat

256

14 Sun

257

258

16 Tue

Independence Day (Mexico) 259

17 Wed

260

18 Thu

Independence Day (Chile) 261

19 Fri

262

20 Sat

263

21 Sun

264

M. Faraday—1791

265

23 Tue

266

24 Wed

267

25 Thu

268

26 Fri

269

27 Sat

270

28 Sun

271

# SEPTEMBER 29 Mon
## 2003 Week 40

E. Fermi—1901 272

## 30 Tue

OSA, Orlando, FL 273

# OCTOBER 1 Wed
## 2003

Founding Day (Peoples Rep. of China) 274

## 2 Thu

275

## 3 Fri

Tag der deutchen Einheit (Germany)
Nat. Foundation Day (Rep. of Korea) 276

## 4 Sat

277

## 5 Sun

Republic Day (Portugal) 278

6 Mon

Yom Kippur (begins sunset previous day) 279

7 Tue

ECLIM, Moscow
N. Bohr—1885 280

8 Wed

281

9 Thu

282

10 Fri

Nat. Holiday (Rep. of China) 283

11 Sat

284

12 Sun

Dia de la Hispanidad (Spain) 285

Colombus Day (US)

286

14 Tue

287

15 Wed

Thanksgiving Day (Canada)

288

16 Thu

289

17 Fri

290

18 Sat

291

19 Sun

292

293
21 Tue

294
22 Wed

295
23 Thu

296
24 Fri

297
25 Sat

298
26 Sun

Return to Standard Time (US)
(set clock back 1 h at 0200 Mon. Morning) 299

APS Plasma Phys., Albuquerque, NM

First Day of Ramadan (begins sunset previous day) 300

28 Tue

301

29 Wed

302

30 Thu

303

31 Fri

304

NOVEMBER 2003 1 Sat

305

2 Sun

306

307

4 Tue

308

5 Wed

Guy Fawkes Day (UK)

309

6 Thu

310

7 Fri

M. Curie—1867

311

8 Sat

312

9 Sun

313

314

11 Tue

Armistice Day
Independence Day (Poland)

315

12 Wed

316

13 Thu

317

14 Fri

318

15 Sat

Republic Day (Brazil)

319

16 Sun

320

321

18 Tue

322

19 Wed

Busstag (Germany) 323

20 Thu

Mexican Revolution Day 324

21 Fri

325

22 Sat

326

23 Sun

Labor Thanksgiving Day (Japan) 327

328

25 Tue

Last Day of Ramadan (begins sunset previous day) 329

26 Wed

330

27 Thu

Thanksgiving Day (US) 331

28 Fri

332

29 Sat

333

30 Sun

334

335

2 Tue

336

3 Wed

337

4 Thu

338

5 Fri

W. Heisenberg—1901

339

6 Sat

Independence Day (Finland)

340

7 Sun

341

342

9 Tue

343

10 Wed

344

11 Thu

345

12 Fri

346

13 Sat

347

14 Sun

348

H. Becquerel—1852 349

16 Tue

350

17 Wed

351

18 Thu

J. Thomson—1852 352

19 Fri

A. Michelson—1852 353

20 Sat

Hanakah (begins sunset previous day) 354

21 Sun

355

356

23 Tue

Emperor's Birthday (Japan) 357

24 Wed

358

25 Thu

Christmas

I. Newton—1642 359

26 Fri

Boxing Day (UK, Canada, Australia) 360

27 Sat

J. Kepler—1571 361

28 Sun

362

DECEMBER 29 Mon
2003 Week 1

363

30 Tue

364

31 Wed

LG-3 365

JANUARY 1 Thu
2004

New Years Day 1

2 Fri

Holiday (Scotland) 2

3 Sat

3

4 Sun

4

## International Time and Country Codes

Numbers in square brackets [ ] are the number of hours that must be added to local time to obtain Greenwich (Universal) Time. Countries with negative numbers lie to the east of Greenwich, England; countries with positive numbers lie to the west. Times [ ] are (winter) standard times. Daylight saving (summer) time variations require 1 hour adjustments when used.

Telephone country codes are listed after the [ ] (e.g., 54 for Argentina, etc.).

Argentina [+3] 54
Armenia [-3] 374
Australia [-8 to -10] 61
  Sidney [-10]
Austria [-1] 43
Azerbijan [-4] 994
Belarus [-2] 375
Belgium [-1] 32
Brazil [+3] 55
Bulgaria [-2] 359
Canada [+4 to +8] 1
Chile [+4] 56
People's Republic of China [-8] 86
Republic of China (Taiwan) [-8] 886
Columbia [+5] 57
Costa Rica [+6] 506
Croatia [-1] 385
Cuba [+5] 53
Czech Republic [-1] 420
Denmark [-1] 45
Egypt [-2] 20
Finland [-2] 358
France [-1] 33
Georgia [-3] 995
Germany [-1] 49
Greece [-2] 30
Hungary [-1] 36
India [-5.5] 91
  Calcutta [-6.5]
Indonesia [-7] 62
Iran [-3.5] 98
Ireland [0] 353
Israel [-2] 972
Italy [-1] 39
Japan [-9] 81
Korea [-9] 82
Mexico [+6 to +8] 52
  Mexico City [+6]
Mongolia [-8] 976
Netherlands [-1] 31
Norway [-1] 47
Pakistan [-5] 92
Peru [+5] 51
Poland [-1] 48
Portugal [0] 351
Romania [-2] 40

Russia [-3 to -12] 7
  Moscow [-3]
  Novosibirsk [-7]
  St. Petersburg [-3]
Slovakia [-1] 421
Slovenia [-1] 386
South Africa [-2] 27
Spain [-1] 34
Sweden [-1] 46
Switzerland [-1] 41
Turkey [-2] 90
Ukraine [-2] 380
United Kingdom [0] 44
United States
  [+5 to +10] 1
    Berkeley [+8]
    Denver [+7]
    Chicago [+6]
    New York [+5]
    Honolulu [+10]

## List of Facilities

1. Advanced Light Source (ALS), Lawrence Berkeley National Laboratory, Berkeley, California, USA:
http://www-als.lbl.gov/als/

2. Advanced Photon Source (APA), Argonne National Laboratory, Argonne, Illinois, USA:
http://epics.aps.anl.gov/welcome.html

3. Angströmquelle Karlsruhe GMBH (ANKA), Forschungszentrum Karlsruhe, Karlsruhe, Germany:
http://www.fzk.de/anka/welcome.html

4. Aarhus Storage Ring in Denmark (ASTRID), Institute for Storage Ring Facilities, Aarhus, Denmark:
http://www.isa.au.dk/

5. Beijing Synchrotron Radiation Facility (BSRF), Institute of High Energy Physics, Beijing, People's Republic of China:
http://www.friends-partners.org/~china/ins/IHEP/bsrf/bsrf.html and http://www.ihep.ac.cn/zzjg/bsrf/bsrf.html

6. Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung m.b.H.(BESSY), Berlin, Germany:
http://www.bessy.de

7. Canadian Light Source, Saskatoon, Saskatchewan, Canada:
http://cls.usask.ca/

8. Center for Advanced Microstructures and Devices (CAMD), Louisiana State University, Baton Rouge, Louisiana, USA:
http://www.camd.lsu.edu/

9. Cornell High Energy Synchrotron Source (CHESS), Cornell University, Ithaca, New York, USA: http://www.tn.cornell.edu/

10. Dafne, Laboratori Nazionali di Frascati, Frascati (Rome), Italy: http://www.lnf.infn.it/

11. Dortmund Electron Test Accelerator (DELTA), University of Dortmund, Dortmund, Germany:
http://www.delta.uni-dortmund.de/home_e.html

12. Electron Linac Facility (NIJI-II, NIJI-IV, TERAS), Electrotechnical Laboratory, Tsukuba, Japan: http://www.etl.go.jp:8080/etl/linac/e/

13. Electron Stretcher Accelerator (ELSA), University of Bonn, Bonn, Germany: http://www-elsa.physik.uni-bonn.de/

14. Elettra Synchrotron Light Source, Trieste, Italy: http://www.elettra.trieste.it/

15. European Synchrotron Radiation Facility (ESRF), Grenoble, France: http://www.esrf.fr/

16. Free Electron Laser Laboratory, Duke University, Durham, North Carolina, USA: http://www.fel.duke.edu/

17. Hamburger Synchrotronstrahlungslabor (HASYLAB), Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany: http://www-hasylab.desy.de/

18. Hiroshima Synchrotron Radiation Center (HISOR), Higashi-Hiroshima, Japan: http://www.hiroshima-u.ac.jp/Organization/src.html

19. Indus 1 and 2, Center for Advanced Technology, Indore, India: http://www.ee.ualberta.ca/ naik/cataccel.html.

20. Kurchatov Synchrotron Radiation Source (KSRS), Kurchatov Institute, Moscow, Russia: http://www.kiae.ru/

21. Kyoto Storage Ring, Institute for Chemical Research, Kyoto University, Uji, Kyoto, Japan: http://wwwal.kuicr.kyoto-u.ac.jp /www/Buttons-e.imagemap?90,64

22. Laboratoire pour l'Utilisation du Rayonnement Electromagntique (LURE), Orsay, France: http://www.lure.u-psud.fr/

23. Laboratrio Nacional de Luz Sincrotron (LNLS),Campinas, So Paulo, Brazil: http://www.lnls.br/

24. MAX-Lab, Lund University, Lund, Sweden: http://www.maxlab.lu.se/

25. Nano-Hana Project, Ichihara, Japan:
http://www.iijnet.or.jp/NANO-HANA/en.html

26. National Synchrotron Light Source (NSLS), Brookhaven National Laboratory, Upton, New York, USA:
http://www.nsls.bnl.gov/

27. National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China, Hefei, Anhui, China:
http://www.ustc.edu.cn/en/srl.htm

28. National Synchrotron Research Center (NSRC), Suranareee University of Technology, Nakhon Ratchasima, Thailand:
http://sut2.sut.ac.th/

29. NewSubaru, Laboratory for Advanced Science and Technology for Industry, Himeji Institute of Technology, Nishi-Harima, Hyogo, Japan:
http://www.lasti.himeji-tech.ac.jp/NS/Index.html

30. Photon Factory (PF), Institute of Materials Structure Science, KEK, Tsukuba, Japan: http://pfwww.kek.jp/

31. Pohang Light Source (PLS), Pohang Accelerator Laboratory, Pohang, Korea: http://pal.postech.ac.kr/

32. Ritsumeikan University Synchrotron Radiation Center, Kusatsu, Shiga, Japan:
http://www.ritsumei.ac.jp/se/d11/index-e.html

33. Siberian Synchrotron Radiation Centre (SSRC), Budker Institute of Nuclear Physics, Novosibirsk, Russia:
http://ssrc.inp.nsk.su/

34. Singapore Synchrotron Light Source, National University of Singapore, Singapore:
http://www.nus.edu.sg/NUSinfo/SSLS/

35. Spring-8, Japanese Synchrotron Radiation Research Institute, Nishi-Harima, Hyogo, Japan: http://www.spring8.or.jp/

36. Stanford Synchrotron Radiation Laboratory (SSRL), Stanford Linear Accelerator Center, Menlo Park, California, USA:
http://www-ssrl.slac.stanford.edu/

37. Swiss Light Source (SLS), Paul Scherrer Institut, Villigen, Switzerland: http://www1.psi.ch/www_sls_hn//

38. Synchrotron Light Laboratory (LLS), Barcelona, Spain: http://www.lls.ifae.es/

39. Synchrotron Radiation Center (SRC), University of Wisconsin, Stoughton, Wisconsin, USA: http://www.src.wisc.edu/

40. Synchrotron Radiation Source (SRS), CCLRC Daresbury Laboratory, Daresbury, United Kingdom: http://srs.dl.ac.uk/index.htm

41. Synchrotron Radiation Research Center (SRRC), Hsinchu, Taiwan, Republic of China: http://www.srrc.gov.tw/en/main2000.htm

42. Synchrotron Ultraviolet Radiation Facilty (SURF III), National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA: http://physics.nist.gov/MajResFac/SURF/SURF.html

43. UVSOR Facility, Institute for Molecular Science, Myodanji, Okazaki, Japan: http://www.uvsor.ims.ac.jp/

44. VSX Light Source, Synchrotron Radiation Laboratory, University of Tokyo Kashiwa Campus, Chiba, Japan: http://www.issp.u-tokyo.ac.jp/labs/sor/index-e.html

## Lithography

Minimum printable line width:

$$L_{\mathrm{w}} = k_1 \frac{\lambda}{\mathrm{NA}} \tag{10.1}$$

where $k_1$ is a constant dominated by the optical system, but affected by pattern transfer processes.

Depth of focus:

$$\mathrm{DOF} = \pm k_2 \frac{\lambda}{(\mathrm{NA})^2} \tag{10.2}$$

Degree of partial coherence:

$$\sigma = \frac{\mathrm{NA_{cond}}}{\mathrm{NA_{obj}}} \tag{10.3}$$

where the subscript cond refers to the condenser or illumination optics, and obj refers to the objective lens of the reduction optics.

Two-year cycle for semiconductors

| | Years | | | | |
|---|---|---|---|---|---|
| | 2001 | 2003 | 2005 | 2007 | 2009 |
| 1:1 lines (nm) | 130 | 90 | 70 | 50 | 35 |
| Isolated lines (nm) | 90 | 60 | 45 | 35 | 25 |

## Zone Plate Optics

Zone radii:

$$r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4} \tag{9.9}$$

$$r_n \simeq \sqrt{n\lambda f} \quad (\mathrm{NA} \ll 1) \tag{9.103}$$

Lens diameter:

$$D \simeq 4N\Delta r \tag{9.13}$$

Focal length:

$$f \simeq \frac{4N(\Delta r)^2}{\lambda} \tag{9.14}$$

Numerical aperture:

$$\mathrm{NA} \simeq \frac{\lambda}{2\Delta r} \tag{9.15}$$

$F$ # of lens:

$$\mathrm{F}^{\#} \simeq \frac{\Delta r}{\lambda} \tag{9.16}$$

Rayleigh criterion

$$\Delta r_{\mathrm{Rayl.}} = \frac{0.610\lambda}{\mathrm{NA}} \tag{9.47}$$

$$\Delta r_{\mathrm{Rayl.}} = 1.22\mathrm{F}^{\#}\lambda = 1.22\Delta r \tag{9.48}$$

where $\Delta r$ = outermost zone width. Note that spatial resolution depends on the illumination partial coherence, $\sigma$ [see Eq. (10.3)].

Depth of focus:

$$\Delta z = \pm\frac{1}{2}\frac{\lambda}{(\mathrm{NA})^2} \tag{9.50}$$

$$\Delta z = \pm 2\mathrm{F}^{\#2}\lambda = \pm 2(\Delta r)^2/\lambda \tag{9.51}$$

Maximum spectral bandwidth condition:

$$\frac{\Delta\lambda}{\lambda} \le \frac{1}{N} \tag{9.52}$$

The far-field diffraction pattern for a uniformly and coherently illuminated pinhole of diameter $d = 2a$ has its first intensity null at $ka\theta = 3.832$, or half angle

$$\theta_{\mathrm{null}} = \frac{0.610\lambda}{a} = \frac{1.22\lambda}{d} \tag{9.36}$$

## EUV/Soft X-Ray Lasers

Growth of stimulated emission:

$$\frac{I}{I_0} = e^{GL} \tag{7.2}$$

where $L$ is the laser length and $G$ is the gain per unit length. For an upper state ion density $n_u$ and a density inversion factor $F(\leq 1)$

$$G = n_u \sigma_{\text{stim}} F \tag{7.4}$$

Where the cross section for stimulated emission is

$$\sigma_{\text{stim}} = \frac{\lambda^3 A_{u\ell}}{8\pi c(\Delta\lambda/\lambda)} \tag{7.16}$$

$$\sigma_{\text{stim}} = \frac{\pi \lambda r_e}{(\Delta\lambda/\lambda)} \left(\frac{g_\ell}{g_u}\right) f_{\ell u} \tag{7.18}$$

where $A_{u\ell}$ is the spontaneous decay rate, $f_{\ell u}$ is the oscillator strength and $g_\ell/g_u$ is the ratio of degeneracy factors.

Power per unit volume laser scaling for pumping and emission:

$$\frac{P}{A} = \frac{16\pi^2 c^2 \hbar(\Delta\lambda/\lambda)GL}{\lambda^4} \tag{7.22}$$

Doppler broadened linewidth:

$$\left.\frac{(\Delta\lambda)}{\lambda}\right|_{\text{FWHM}} = \frac{v_i}{c} = \frac{2\sqrt{2\ln 2}}{c}\sqrt{\frac{\kappa T_i}{M}} \tag{7.19a}$$

where $v_i$ is the ion thermal velocity, $\kappa T_i$ is the ion temperature, and $M$ is the ion mass. with $\kappa T_i$ expressed in eV and an ion mass of $2m_p Z$

$$\left.\frac{(\Delta\lambda)}{\lambda}\right|_{\text{FWHM}} = 7.68 \times 10^{-5} \left(\frac{\kappa T_i}{2Z}\right)^{1/2} \tag{7.19b}$$

## Coherence

Longitudinal coherence length:

$$\ell_{\text{coh}} = \lambda^2/2\Delta\lambda \tag{8.3}$$

Spatial or transverse coherence (rms quantities):

$$d \cdot \theta = \lambda/2\pi \tag{8.5}$$

or in terms of FWHM values

$$d \cdot 2\theta|_{\text{FWHM}} = 0.44\lambda$$

Spatially coherent power within a relative spectral bandwidth $\lambda/\Delta\lambda = N$ for an undulator with $N$ periods:

$$\bar{P}_{\text{coh},N} = \frac{e\lambda_{\text{u}} I}{8\pi\epsilon_0 d_x d_y \theta_x \theta_y \gamma^2} \cdot \left(\frac{\hbar\omega_0}{\hbar\omega} - 1\right) f(\hbar\omega/\hbar\omega_0) \tag{8.7c}$$

where $\hbar\omega_0$ corresponds to $K = 0$, and where

$$f(\hbar\omega/\hbar\omega_0) = \frac{7}{16} + \frac{5}{8}\frac{\hbar\omega}{\hbar\omega_0} - \frac{1}{16}\left(\frac{\hbar\omega}{\hbar\omega_0}\right)^2 + \ldots \tag{8.8}$$

When the undulator condition ($\sigma' \ll \theta_{\text{cen}}$) is satisfied, the coherent power within a relative spectral bandwidth $\Delta\lambda/\lambda < 1/N$, is

$$\bar{P}_{\text{coh},\lambda/\Delta\lambda} = \frac{e\lambda_{\text{u}} I \eta(\lambda/\Delta\lambda) N^2}{8\pi\epsilon_0 d_x d_y} \cdot \left(1 - \frac{\hbar\omega}{\hbar\omega_0}\right) f(\hbar\omega/\hbar\omega_0)$$

$$(\sigma'^2 \ll \theta_{\text{cen}}^2) \tag{8.10c}$$

where $\eta$ is the combined beamline and monochrometer efficiency.

Spatially coherent power available from a laser is

$$P_{\text{coh}} = \frac{(\lambda/2\pi)^2}{(d_x\theta_x)(d_y\theta_y)} P_{\text{laser}} \tag{8.11}$$

where $P_{\text{laser}}$ is the total laser power.

Normalized degree of spatial coherence, or complex coherence factor:

$$\mu_{12} = \frac{\langle E_1(t)E_2^*(t)\rangle}{\sqrt{\langle |E_1|^2\rangle}\sqrt{\langle |E_2|^2\rangle}} \tag{8.12}$$

The van Cittert-Zernike theorem for the complex coherence factor is

$$\mu_{OP} = \frac{e^{-i\psi}\int\int I(\xi,\eta)e^{ik(\xi\theta_x+\eta\theta_y)}\,d\xi\,d\eta}{\int\int I(\xi,\eta)\,d\xi\,d\eta} \tag{8.19}$$

For a uniformly but incoherently illuminated pinhole

$$\mu_{OP}(\theta) = e^{-i\psi}\frac{2J_1(ka\theta)}{(ka\theta)} \tag{8.27}$$

which has its first null ($\mu_{OP} = 0$) at $ka\theta = 3.832$, which for $d = 2a$ corresponds to $d \cdot \theta = 1.22\lambda$.

## Plasma Equations

Electron plasma frequency:

$$\omega_p^2 = \frac{e^2 n_e}{\epsilon_0 m} \tag{6.5}$$

Debye screening distance:

$$\lambda_D = \left(\frac{\epsilon_0 \kappa T_e}{e^2 n_e^2}\right)^{1/2} \tag{6.6}$$

No. of electrons in Debye sphere:

$$N_D = \frac{4\pi}{3}\lambda_D^3 n_e \tag{6.7}$$

Electron cyclotron frequency:

$$\omega_c = \frac{eB}{m} \tag{6.8}$$

Maxwellian velocity distribution for electrons characterized by a single electron temperature $\kappa T_e$:

$$f(\mathrm{v}) = \frac{1}{(2\pi)^{3/2}\mathrm{v}_e^3}\, e^{-\mathrm{v}^2/2\mathrm{v}_e^2} \tag{6.1}$$

where

$$\mathrm{v}_e = \left(\frac{\kappa T_e}{m}\right)^{1/2} \tag{6.2}$$

Electron sound speed:

$$a_e = \left(\frac{\gamma \kappa T_e}{m}\right)^{1/2} \tag{6.79}$$

Critical electron density:

$$n_c \equiv \frac{\epsilon_0 m \omega^2}{e^2} = 1.11 \times 10^{21}\ \frac{\mathrm{e/cm^3}}{\lambda^2(\mu\mathrm{m})} \qquad (6.112\mathrm{a}\,\&\,\mathrm{b})$$

Refractive index of plasma is

$$n = \sqrt{1 - \frac{n_e}{n_c}} \tag{6.114b}$$

Ratio of electron energy in coherent oscillations to that in random motion:

$$\left|\frac{\mathrm{v_{os}}}{\mathrm{v_e}}\right|^2 = \frac{e^2E^2}{m\omega^2\kappa T_e} = \frac{I/c}{n_c\kappa T_e} \tag{6.131a}$$

$$\left|\frac{\mathrm{v_{os}}}{\mathrm{v_e}}\right|^2 = \frac{0.021I(10^{14}\ \mathrm{W/cm^2})\lambda^2\ (\mu\mathrm{m})}{\kappa\mathrm{T_e(keV)}} \tag{6.131b}$$

Spectral brightness of blackbody radiation within $\Delta\omega/\omega = 0.1\%\mathrm{BW}$:

$$B_{\Delta\omega/\omega} =$$

$$3.146 \times 10^{11} \left(\frac{\kappa T}{eV}\right)^3 \frac{(\hbar\omega/\kappa T)^3}{(e^{\hbar\omega/\kappa T} - 1)} \frac{\mathrm{photons/sec}}{(\mathrm{mm})^2(\mathrm{mr})^2(0.1\%\mathrm{BW})} \tag{6.136b}$$

Photon energy at peak spectral brightness:

$$\hbar\omega\,|_{\mathrm{pk}} = 2.822\kappa T \tag{6.137}$$

where $\kappa$ is the Boltzmann constant.

Stefan-Boltzmann radiation law (blackbody intensity at any interface):

$$I = \sigma T^4 \tag{6.141b}$$

where the Stefan-Boltzmann constant is

$$\sigma = \frac{\pi^2\kappa^4}{60c^2\hbar^3} \tag{6.142}$$

with $\kappa T$ in eV:

$$I = \widehat{\sigma}(\kappa T)^4 \tag{6.143a}$$

where $\widehat{\sigma}$ is the modified Stefan-Boltzmann constant

$$\widehat{\sigma} = \frac{\pi^2}{60\hbar^3c^2} = 1.027 \times 10^5 \frac{\mathrm{watts}}{\mathrm{cm^2(eV)^4}} \tag{6.143b}$$

## Wiggler Radiation

Critical harmonic number

$$n_c = \frac{3K}{4}\left(1 + \frac{K^2}{2}\right) \tag{5.82}$$

for large $K$:

$$n_c \simeq \frac{3K^3}{8}, \quad K \gg 1 \tag{5.83}$$

Total radiated power from a wiggler is

$$P_T = \frac{\pi e K^2 \gamma^2 I N}{3\epsilon_0 \lambda_u} \tag{5.85a}$$

$$P_T(\mathrm{W}) = \frac{1.90 \times 10^{-6} K^2 \gamma^2 N I(\mathrm{A})}{\lambda_u(\mathrm{cm})} \tag{5.85b}$$

On axis wiggler photon flux per unit solid angle, per unit relative spectral bandwidth:

$$\left.\frac{d^2F}{d\Omega d\omega/\omega}\right|_0 =$$

$$2.65 \times 10^{13} N E_e^2(\mathrm{GeV}) I(\mathrm{A}) H_2(E/E_c) \frac{\text{photons/sec}}{(\text{mrad})^2 (0.1\%\text{BW})} \tag{5.86}$$

The vertically integrated flux is

$$\frac{d^2F}{d\theta d\omega/\omega} =$$

$$4.92 \times 10^{13} N E_e(\mathrm{GeV}) I(\mathrm{A}) G_1(E/E_c) \frac{\text{photons/s}}{(\text{mrad}) \cdot (0.1\%\text{BW})} \tag{5.87}$$

## Undulator Radiation

Undulator equation

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \tag{5.28}$$

where

$$K = eB_0\lambda_u/2\pi mc = 0.9337 B_0(T)\lambda_u(\mathrm{cm}) \tag{5.18a \& b}$$

Undulator photon energy and wavelength in practical units at $\theta = 0$:

$$E\ (\mathrm{keV}) = \frac{(0.9496)E_e^2\ (\mathrm{GeV})}{\lambda_u\ (\mathrm{cm})\left(1 + \frac{K^2}{2}\right)} \tag{5.29b}$$

$$\lambda\ (\mathrm{nm}) = \frac{(1.306)\lambda_u\ (\mathrm{cm})\left(1 + \frac{K^2}{2}\right)}{E_e^2\ (\mathrm{GeV})} \tag{5.29a}$$

Central radiation cone:

$$\theta_{\mathrm{cen}} = \frac{1}{\gamma^*\sqrt{N}} = \frac{\sqrt{1 + \frac{K^2}{2}}}{\gamma\sqrt{N}} \tag{5.32}$$

Defined as containing a spectral bandwidth

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{N} \tag{5.14}$$

Power within the central cone:

$$\bar{P}_{\mathrm{cen}} = \frac{\pi e\gamma^2 I}{\epsilon_0\lambda_u}\frac{K^2}{\left(1 + \frac{K^2}{2}\right)^2}f(K) \tag{5.41a}$$

$$\bar{P}_{\mathrm{cen}} = (5.69 \times 10^{-6}\mathrm{W})\frac{\gamma^2 I(\mathrm{A})}{\lambda_u(\mathrm{cm})}\frac{K^2}{\left(1 + \frac{K^2}{2}\right)^2}f(K) \tag{5.41b}$$

for $K \ll 1$, $f(K) \cong 1$; for $K = 1$, $f(K) = 0.828$.

Radiation cone half angles for finite electron beam divergence:

$$\theta_{Tx} = \sqrt{\theta_{\text{cen}}^2 + \sigma_x'^2} \tag{5.56a}$$

$$\theta_{Ty} = \sqrt{\theta_{\text{cen}}^2 + \sigma_y'^2} \tag{5.56b}$$

Spectral brightness in practical units (assumes $\sigma'^2 \ll \theta_{\text{cen}}^2$):

$$B_{\Delta\omega/\omega}(0) = \frac{(7.25 \times 10^6)\gamma^2 N^2 I(\text{A})}{\sigma_x(\text{mm})\sigma_y(\text{mm})\left(1 + \frac{\sigma_x'^2}{\theta_{\text{cen}}^2}\right)^{1/2}\left(1 + \frac{\sigma_y'^2}{\theta_{\text{cen}}^2}\right)^{1/2}}$$

$$\times \frac{K^2 f(K)}{\left(1 + \frac{K^2}{2}\right)^2} \frac{\text{ph/sec}}{(\text{mm})^2(\text{mrad})^2(0.1\%\text{BW})} \tag{5.65}$$

## Synchotron Radiation

Forward cone half angle for synchrotron radiation:

$$\theta \simeq \frac{1}{2\gamma} \tag{5.2}$$

Relativistic (Lorentz) transformation factor:

$$\gamma \equiv 1/(1 - v^2/c^2)^{1/2}$$

In terms of the electron energy

$$\gamma = \frac{E_e}{mc^2} = 1957\ E_e\ (\mathrm{GeV}) \tag{5.5}$$

Bending magnet radius in meters:

$$\rho(m) = \frac{1.7045}{B(T)} \left(\frac{\gamma}{1000}\right)$$

Critical photon energy:

$$E_c = \hbar\omega_c = \frac{3e\hbar B\gamma^2}{2m} \tag{5.7a}$$

$$E_c(\mathrm{keV}) = 0.6650 E_e^2(\mathrm{GeV}) B(\mathrm{T}) \tag{5.7b}$$

Critical wavelength:

$$\lambda_c = \frac{4\pi mc}{3eB\gamma^2} \tag{5.7c}$$

$$\lambda_c\ (\mathrm{nm}) = \frac{1.864}{E_e^2(\mathrm{GeV})B(\mathrm{T})} \tag{5.7d}$$

Photon flux from a bending magnet (on axis):

$$\left.\frac{d^3F_B}{d\theta d\psi d\omega/\omega}\right|_{\psi=0} =$$

$$1.33 \times 10^{13} E_e^2\ (\mathrm{GeV}) I(\mathrm{A}) H_2(E/E_c) \frac{\mathrm{photons/sec}}{(\mathrm{mrad})^2\ (0.1\%\ \mathrm{BW})} \tag{5.6}$$

Vertically integrated flux (all $\psi$):

$$\frac{d^2F_B}{d\theta d\omega/\omega} = 2.46 \times 10^{13} E_e(\mathrm{GeV}) I(\mathrm{A}) G_1(E/E_c) \frac{\mathrm{photons/sec}}{\mathrm{mrad}(0.1\%\ \mathrm{BW})} \tag{5.8}$$

## Multilayer Mirrors

Bragg's law:

$$m\lambda = 2d \sin\theta \tag{4.6b}$$

Correction for refraction:

$$m\lambda = 2d\sin\theta\sqrt{1-\frac{2\bar{\delta}}{\sin^2\theta}} = 2d\sin\theta\left(1-\frac{4\bar{\delta}d^2}{m^2\lambda^2}\right)$$

where $\bar{\delta}$ is the single period weighted real part of the refractive index.

$$\Gamma = \frac{\Delta t_{\mathrm{H}}}{\Delta t_{\mathrm{H}} + \Delta t_{\mathrm{L}}} = \frac{\Delta t_{\mathrm{H}}}{d} \tag{4.7}$$

Reflective Optics

Tangential focus: $1/u + 1/v = 2/r\cos(\theta)$
Saggital focus: $1/u + 1/v = 2\cos(\theta)/r$

where $u$ is the source distance, $v$ is the image distance, and $r$ is the radius of curvature of mirror.

## X-Ray Scattering and Absorption

Thomson cross section for a free electron:

$$\sigma_e = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-25}\text{cm} \tag{2.45}$$

$$r_e = \frac{e^2}{4\pi\epsilon_0 mc^2} = 2.82 \times 10^{-13}\text{cm} \tag{2.44}$$

and $r_e$ is the classical electron radius.

Scattering cross section for a bound electron:

$$\sigma = \frac{8\pi}{3} r_e^2 \frac{\omega^4}{(\omega^2 - \omega_s^2)^2 + (\gamma\omega)^4} \tag{2.51}$$

Rayleigh cross section ($\omega^2 \ll \omega_s^2$):

$$\sigma_R = \frac{8\pi}{3} r_e^2 \left(\frac{\omega}{\omega_s}\right)^4 = \frac{8\pi}{3} r_e^2 \left(\frac{\lambda_s}{\lambda}\right)^4 \tag{2.52}$$

Scattering by a multi-electron atom:

$$\frac{d\sigma(\omega)}{d\Omega} = r_e^2 |f|^2 \sin^2\Theta \tag{2.68}$$

$$\sigma(\omega) = \frac{8\pi}{3} |f|^2 r_e^2 \tag{2.69}$$

where the complex atomic scattering factor represents the electric field scattered by an atom, normalized to that of a single electron:

$$f(\Delta\mathbf{k}, \omega) = \sum_{s=1}^{Z} \frac{\omega^2 e^{-i\Delta\mathbf{k}\cdot\Delta\mathbf{r}_s}}{(\omega^2 - \omega_s^2 + i\gamma\omega)} \tag{2.66}$$

For forward scattering or long wavelength this reduces to

$$f^0(\omega) = \sum_{s=1}^{Z} \frac{\omega^2}{(\omega^2 - \omega_s^2 + i\gamma\omega)} = f_1^0 - i f_2^0 \qquad (2.72)\,\&\,2.79)$$

Refractive index for x-ray radiation is commonly written * as

$$n(\omega) = 1 - \delta + i\beta = 1 - \frac{n_a r_e \lambda^2}{2\pi}(f_1^0 - i f_2^0) \qquad (3.9\,\&\,3.12)$$

where

$$\delta = \frac{n_a r_e \lambda^2}{2\pi} f_1^0(\omega) \qquad (3.13a)$$

$$\beta = \frac{n_a r_e \lambda^2}{2\pi} f_2^0(\omega) \qquad (3.13b)$$

Absorption length in a material:

$$\ell_{\text{abs}} = \frac{\lambda}{4\pi\beta} = \frac{1}{2 n_a r_e \lambda f_2^0(\omega)} \qquad (3.22\,\&\,3.23)$$

Mass dependent absorption coefficient:

$$\mu = \frac{2 r_e \lambda}{A m_u} f_2^0(\omega) \qquad (3.26)$$

Atomic absorption cross section:

$$\sigma_{\text{abs}} = 2 r_e \lambda f_2^0(\omega) = A m_u \mu(\omega) \qquad (3.28a\&b)$$

Relative phase shift through a medium compared to a vacuum:

$$\Delta\phi = \left(\frac{2\pi\delta}{\lambda}\right) \Delta r \qquad (3.29)$$

where $\Delta r$ is the thickness or propagation distance.

Snell's law:

$$\sin\phi' = \frac{\sin\phi}{n} \qquad (3.38)$$

Critical angle for total external reflection of x-rays:

$$\theta_c = \sqrt{2\delta} \qquad (3.41)$$

$$\theta_c = \sqrt{2\delta} = \sqrt{\frac{n_a r_e \lambda^2 f_1^0(\lambda)}{\pi}} \qquad (3.42a)$$

Brewster's angle (or polarizing angle):

$$\phi_{\text{B}} \simeq \frac{\pi}{4} - \frac{\delta}{2} \qquad (3.60)$$

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* The choice of $+i\beta$ is consistent with a wave description $E = E_0 \exp[-i(\omega t - kr)]$. A choice of $-i\beta$ is consistent with $E = E_0 \exp[i(\omega t - kr)]$.

## General X-Ray Formulae

The formulae above and in the preceding pages are equations as numbered in *Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge Univ. Press, 1999) by David Attwood; http://www.coe.berkeley.edu/AST/sxreuv.

Wavelength and photon energy relationship:

$$\hbar\omega \cdot \lambda = hc = 1239.842 \text{ eV} \cdot \text{nm} \tag{1.1}$$

Number of photons required for 1 joule of energy:

$$1 \text{ joule} \Rightarrow 5.034 \times 10^{15} \lambda \text{ [nm] photons} \tag{1.2a}$$

Transmission of photons through a material:

$$\frac{I}{I_0} = e^{-\rho\mu x} \tag{1.3a}$$

where $\mu$ is the mass absorption coefficient; $\rho$ is the mass density.

Or

$$\frac{I}{I_0} = e^{-n_a \sigma_{\text{abs}} x} \tag{1.3b}$$

where $\sigma$ = photoionization cross section; $n_a$ is the atomic density.

Maxwell's equations in vacuum (mks):

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \tag{2.1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2.2}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2.3}$$

$$\nabla \cdot \mathbf{D} = \rho \tag{2.4}$$

where

$$\mathbf{D} = \epsilon_0 \mathbf{E} \tag{2.5}$$

$$\mathbf{B} = \mu_0 \mathbf{H} \tag{2.6}$$

Speed of light in a vacuum:

$$c \equiv \frac{1}{\sqrt{\epsilon_0 \mu_0}} \tag{2.8}$$

Electronic field associated with a radiated wave in vacuum:

$$\mathbf{E}(\mathbf{r}, t) = \frac{e\mathbf{a}_T\left(t - \frac{r}{c}\right)}{4\pi\epsilon_0 c^2 r} \tag{2.25}$$

Power radiated per unit solid angle:

$$\frac{dP}{d\Omega} = \frac{e^2|\mathbf{a}|^2 \sin^2\Theta}{16\pi^2\epsilon_0 c^3} \tag{2.34}$$

Total power radiated by an oscillating electron of acceleration **a**:

$$P = \frac{8\pi}{3}\left(\frac{e^2|\mathbf{a}|^2}{16\pi^2\epsilon_0 c^3}\right) \tag{2.36}$$

$$a_0 = 0.529 \text{ Å}; \;\; \pi a_0^2 = 8.8 \times 10^{-17}\text{cm}^2$$

$$N_A = 6.0221 \times 10^{23} \text{ molecules/mole}$$

$$n_L = 2.7 \times 10^{19}\text{molecules/cm}^3 \text{ at } 0° \text{ C}$$

$$r_n = \frac{n^2 a_0}{Z}; \;\; \Delta E = Z^2(13.6 \text{ eV})\left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right)$$

*Table I* *Electron binding energies, in electron volts, for the elements in their natural forms.*

| Element | K 1s | $L_1$ 2s | $L_2$ $2p_{1/2}$ | $L_3$ $2p_{3/2}$ | $M_1$ 3s | $M_2$ $3p_{1/2}$ | $M_3$ $3p_{3/2}$ | $M_4$ $3d_{3/2}$ | $M_5$ $3d_{5/2}$ | $N_1$ 4s | $N_2$ $4p_{1/2}$ | $N_3$ $4p_{3/2}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H | 13.6 | | | | | | | | | | | |
| 2 He | 24.6* | | | | | | | | | | | |
| 3 Li | 54.7* | | | | | | | | | | | |
| 4 Be | 111.5* | | | | | | | | | | | |
| 5 B | 188* | | | | | | | | | | | |
| 6 C | 284.2* | | | | | | | | | | | |
| 7 N | 409.9* | 37.3* | | | | | | | | | | |
| 8 O | 543.1* | 41.6* | | | | | | | | | | |
| 9 F | 696.7* | | | | | | | | | | | |
| 10 Ne | 870.2* | 48.5* | 21.7* | 21.6* | | | | | | | | |
| 11 Na | 1070.8† | 63.5† | 30.65† | 30.81* | | | | | | | | |
| 12 Mg | 1303.0† | 88.7* | 49.78† | 49.50† | | | | | | | | |
| 13 Al | 1559.6 | 117.8* | 72.95* | 72.55* | | | | | | | | |
| 14 Si | 1839 | 149.7*b | 99.82* | 99.42* | | | | | | | | |
| 15 P | 2145.5 | 189* | 136* | 135* | | | | | | | | |
| 16 S | 2472 | 230.9 | 163.6* | 162.5* | | | | | | | | |
| 17 Cl | 2822.4 | 270 | 202* | 200* | | | | | | | | |
| 18 Ar | 3205.9* | 326.3* | 250.6† | 248.4* | 29.3* | 15.9* | 15.7* | | | | | |
| 19 K | 3608.4* | 378.6* | 297.3* | 294.6* | 34.8* | 18.3* | 18.3* | | | | | |
| 20 Ca | 4038.5* | 438.4† | 349.7† | 346.2† | 44.3 † | 25.4† | 25.4† | | | | | |
| 21 Sc | 4492 | 498.0* | 403.6* | 398.7* | 51.1* | 28.3* | 28.3* | | | | | |
| 22 Ti | 4966 | 560.9† | 460.2† | 453.8† | 58.7† | 32.6† | 32.6† | | | | | |

This table courtesy of G.P. Williams, Brookhaven National Laboratory.
See the complete table at http://www-cxro.lbl.gov

| Element | K 1s | $L_1$ 2s | $L_2$ $2p_{1/2}$ | $L_3$ $2p_{3/2}$ | $M_1$ 3s | $M_2$ $3p_{1/2}$ | $M_3$ $3p_{3/2}$ | $M_4$ $3d_{3/2}$ | $M_5$ $3d_{5/2}$ | $N_1$ 4s | $N_2$ $4p_{1/2}$ | $N_3$ $4p_{3/2}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 V | 5465 | 626.7† | 519.8† | 512.1† | 66.3† | 37.2† | 37.2† | | | | | |
| 24 Cr | 5989 | 696.0† | 583.8† | 574.1† | 74.1† | 42.2† | 42.2† | | | | | |
| 25 Mn | 6539 | 769.1† | 649.9† | 638.7† | 82.3† | 47.2† | 47.2† | | | | | |
| 26 Fe | 7112 | 844.6† | 719.9† | 706.8† | 91.3† | 52.7† | 52.7† | | | | | |
| 27 Co | 7709 | 925.1† | 793.2† | 778.1† | 101.0† | 58.9† | 59.9† | | | | | |
| 28 Ni | 8333 | 1008.6† | 870.0† | 852.7† | 110.8† | 68.0† | 66.2† | | | | | |
| 29 Cu | 8979 | 1096.7† | 952.3† | 932.7 | 122.5† | 77.3† | 75.1† | | | | | |
| 30 Zn | 9659 | 1196.2* | 1044.9* | 1021.8* | 139.8* | 91.4* | 88.6* | 10.2* | 10.1* | | | |
| 31 Ga | 10367 | 1299.0*b | 1143.2† | 1116.4† | 159.5† | 103.5† | 100.0† | 18.7† | 18.7† | | | |
| 32 Ge | 11103 | 1414.6*b | 1248.1*b | 1217.0*b | 180.1* | 124.9* | 120.8* | 29.8* | 29.2* | | | |
| 33 As | 11867 | 1527.0*b | 1359.1*b | 1323.6*b | 204.7* | 146.2* | 141.2* | 41.7* | 41.7* | | | |
| 34 Se | 12658 | 1652.0*b | 1474.3*b | 1433.9*b | 229.6* | 166.5* | 160.7* | 55.5* | 54.6* | | | |
| 35 Br | 13474 | 1782* | 1596* | 1550* | 257* | 189* | 182* | 70* | 69* | | | |
| 36 Kr | 14326 | 1921 | 1730.9* | 1678.4* | 292.8* | 222.2* | 214.4 | 95.0* | 93.8* | 27.5* | 14.1* | 14.1* |
| 37 Rb | 15200 | 2065 | 1864 | 1804 | 326.7* | 248.7* | 239.1* | 113.0* | 112* | 30.5* | 16.3* | 15.3 * |
| 38 Sr | 16105 | 2216 | 2007 | 1940 | 358.7† | 280.3† | 270.0† | 136.0† | 134.2† | 38.9† | 21.3† | 20.1† |
| 39 Y | 17038 | 2373 | 2156 | 2080 | 392.0*b | 310.6* | 298.8* | 157.7† | 155.8† | 43.8* | 24.4* | 23.1* |
| 40 Zr | 17998 | 2532 | 2307 | 2223 | 430.3† | 343.5† | 329.8† | 181.1† | 178.8† | 50.6† | 28.5† | 27.1† |
| 41 Nb | 18986 | 2698 | 2465 | 2371 | 466.6† | 376.1† | 360.6† | 205.0† | 202.3† | 56.4† | 32.6† | 30.8† |
| 42 Mo | 20000 | 2866 | 2625 | 2520 | 506.3† | 411.6† | 394.0† | 231.1† | 227.9† | 63.2† | 37.6† | 35.5† |
| 43 Tc | 21044 | 3043 | 2793 | 2677 | 544* | 447.6 | 417.7* | 257.6* | 253.9* | 69.5* | 42.3* | 39.9* |
| 44 Ru | 22117 | 3224 | 2967 | 2838 | 586.1* | 483.5† | 461.4† | 284.2† | 280.0† | 75.0† | 46.3† | 43.2† |
| 45 Rh | 23220 | 3412 | 3146 | 3004 | 628.1† | 521.3† | 496.5† | 311.9† | 307.2† | 81.4*b | 50.5† | 47.3† |
| 46 Pd | 24350 | 3604 | 3330 | 3173 | 671.6† | 559.9† | 532.3† | 340.5† | 335.2† | 87.1*b | 55.7†a | 50.9† |
| 47 Ag | 25514 | 3806 | 3524 | 3351 | 719.0† | 603.8† | 573.0† | 374.0† | 368.3 | 97.0† | 63.7† | 58.3† |

# Periodic Table of the Elements

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 **H** 1.01 | | | | | | | | | | | | | | | | | 2 **He** 4.00 |
| 3 **Li** 6.94 | 4 **Be** 9.01 | | | | | | | | | | | 5 **B** 10.81 | 6 **C** 12.01 | 7 **N** 14.01 | 8 **O** 16.00 | 9 **F** 19.00 | 10 **Ne** 20.18 |
| 11 **Na** 22.99 | 12 **Mg** 24.31 | | | | | | | | | | | 13 **Al** 26.98 | 14 **Si** 28.09 | 15 **P** 30.97 | 16 **S** 32.07 | 17 **Cl** 35.45 | 18 **Ar** 39.95 |
| 19 **K** 39.10 | 20 **Ca** 40.08 | 21 **Sc** 44.96 | 22 **Ti** 47.87 | 23 **V** 50.94 | 24 **Cr** 52.00 | 25 **Mn** 54.94 | 26 **Fe** 55.85 | 27 **Co** 58.93 | 28 **Ni** 58.69 | 29 **Cu** 63.55 | 30 **Zn** 65.39 | 31 **Ga** 69.72 | 32 **Ge** 72.61 | 33 **As** 74.92 | 34 **Se** 78.96 | 35 **Br** 79.90 | 36 **Kr** 83.80 |
| 37 **Rb** 85.47 | 38 **Sr** 87.62 | 39 **Y** 88.91 | 40 **Zr** 91.22 | 41 **Nb** 92.91 | 42 **Mo** 95.94 | 43 **Tc** (98) | 44 **Ru** 101.07 | 45 **Rh** 102.91 | 46 **Pd** 106.42 | 47 **Ag** 107.87 | 48 **Cd** 112.41 | 49 **In** 114.82 | 50 **Sn** 118.71 | 51 **Sb** 121.76 | 52 **Te** 127.60 | 53 **I** 126.90 | 54 **Xe** 131.29 |
| 55 **Cs** 132.91 | 56 **Ba** 137.33 | 57 **La** 138.91 | 72 **Hf** 178.49 | 73 **Ta** 180.95 | 74 **W** 183.84 | 75 **Re** 186.21 | 76 **Os** 190.23 | 77 **Ir** 192.22 | 78 **Pt** 195.08 | 79 **Au** 196.97 | 80 **Hg** 200.59 | 81 **Tl** 204.38 | 82 **Pb** 207.2 | 83 **Bi** 208.98 | 84 **Po** (209) | 85 **At** (210) | 86 **Rn** (222) |
| 87 **Fr** (223) | 88 **Ra** (226) | 89 **Ac** (227) | 104 **Rf** (261) | 105 **Db** (262) | 106 **Sg** (266) | 107 **Bh** (264) | 108 **Hs** (269) | 109 **Mt** (268) | 110 (271) | 111 (272) | 112 (277) | | 114 (285) | | 116 (289) | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lanthanide series | 58 **Ce** 140.12 | 59 **Pr** 140.91 | 60 **Nd** 144.24 | 61 **Pm** (145) | 62 **Sm** 150.36 | 63 **Eu** 151.96 | 64 **Gd** 157.25 | 65 **Tb** 158.93 | 66 **Dy** 162.50 | 67 **Ho** 164.93 | 68 **Er** 167.26 | 69 **Tm** 168.93 | 70 **Yb** 173.04 | 71 **Lu** 174.97 |
| Actinide series | 90 **Th** 232.04 | 91 **Pa** 231.04 | 92 **U** 238.03 | 93 **Np** (237) | 94 **Pu** (244) | 95 **Am** (243) | 96 **Cm** (247) | 97 **Bk** (247) | 98 **Cf** (251) | 99 **Es** (252) | 100 **Fm** (257) | 101 **Md** (258) | 102 **No** (259) | 103 **Lr** (262) |

## 2004

### JANUARY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 29 | 30 | 31 |

### FEBRUARY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 29 | | | | | | |

### MARCH

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 28 | 29 | 30 | 31 | | | |

### APRIL

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 29 | 30 | |

### MAY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | | | 1 |
| 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 30 | 31 | | | | | |

### JUNE

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | 29 | 30 | | | |

### JULY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 29 | 30 | 31 |

### AUGUST

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 29 | 30 | 31 | | | | |

### SEPTEMBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| 26 | 27 | 28 | 29 | 30 | | |

### OCTOBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | | 1 | 2 |
| 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 31 | | | | | | |

### NOVEMBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 28 | 29 | 30 | | | | |

### DECEMBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| 26 | 27 | 28 | 29 | 30 | 31 | |

## 2005

### JANUARY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | | | 1 |
| 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 30 | 31 | | | | | |

### FEBRUARY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | | | | | |

### MARCH

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | 29 | 30 | 31 | | |

### APRIL

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | | 1 | 2 |
| 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 |

### MAY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 29 | 30 | 31 | | | | |

### JUNE

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| 26 | 27 | 28 | 29 | 30 | | |

### JULY

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | | 1 | 2 |
| 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 31 | | | | | | |

### AUGUST

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 28 | 29 | 30 | 31 | | | |

### SEPTEMBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 29 | 30 | |

### OCTOBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | | | 1 |
| 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 30 | 31 | | | | | |

### NOVEMBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | [illegible] | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | 29 | 30 | | | |

### DECEMBER

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 29 | 30 | 31 |