Syllabus for

Physics 330: Advanced Laboratory

Winter Term, 2010
1:00 - 4:00 MWF, Youngchild 126
Instructors: Jeff Collett and Matt Stoneking

Catalog Course Description:

Independent work on experiments selected from the following areas: optical, Mössbauer, alpha, beta, gamma ray, and X-ray spectroscopy; optical double resonance; magnetic resonance; vacuum techniques; solid-state physics; laser physics; nuclear physics.

Course Objectives:

To acquaint students with the practice of experimental physics, the use of contemporary instrumentation, the essence of several landmark experiments, and the basics of machine tool operation. This course should strengthen student skills in conducting experiments, making measurements, documenting lab activities in a notebook, explaining experiments at an elementary level, making formal presentations, and writing a scientific paper.

Required Text:

- *Experiments in Modern Physics*, by Adrian C. Mellissinos and Jim Napolitano, 2nd Edition (Academic Press, 2003). This text serves as an excellent introduction to many of the experiments in the Advanced Lab. Sections of this text will also be assigned as preparation for discussion.

Materials:

Students in this course learn experiments by reference to various sources including journal articles (especially review articles) and instruction manuals. In addition to the required text, the following books may be useful when beginning a new experiment:

- W. Preston and E. R. Dietz, *The Art of Experimental Physics* (one copy in the lab).
- R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles* (one or two copies in the lab).
- *The McGraw-Hill Encyclopedia of Science and Technology* (in the reference section of the library).

The following books will be of occasional use in this course. There are several copies of each in the lab and/or the CPL:

- AIP Style Manual
- D. M. Cook, *Theory of Experiment.*
- P. R. Bevington and D. K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*.
- J. H. Moore, C. C. Davis, and M. A. Coplan, *Building Scientific Apparatus*.

Three-ring binders and other materials set out for each experiment must remain in Youngchild 126 (Atomic & Nuclear Lab), 128 (Laser Palace), 138 (CPL), or 104 (Physics Commons). These resources are irreplaceable and hence cannot leave the department. This course employs a large collection of equipment, NIM modules, multichannel analyzers, digital oscilloscopes, PCs with GPIB interfaces, electronic and optical instrumentation, vacuum hardware, lasers, machine shop tools, the CPL, and on-line literature searching. Physics 330 attempts to acquaint you with these items; notebook entries should confirm this fact.

Precautions:

Exposure to radiation must be minimized. Before using a radioactive source, review the catalog of sources attached to this document for information about its dangers. Machine tools are dangerous; use them only when a supervisor is present. Lasers are also dangerous; heed the precautions reviewed in the laser safety video and contained in the Q&A on Eye Safety with Lasers attached to this document.

Grades:

This course requires initiative, perseverance, and about 20 hours/week of lab time. Assistance from the instructor should be sought mainly during afternoon lab hours (MWF). Food and drinks, *etc.* do not belong in the lab. Incompletes are rarely given in this course. Completion of the major required elements of the course is necessary to receive a passing grade. Final grades will be based on the following weighted components:

1) Notebook* 30 %
2) Paper* 25 %
3) Oral Presentation* 15 %
4) Dialogues 15 %
5) Presentation of a PRL Article 5%
6) Participation (and leading of) discussions 5%
7) Colloquium Attendance 5%

* Each of these required elements must be completed with a satisfactory grade in order to pass the course.

Experiments, Paper and Oral Presentation:

- Each student is required to perform ***four*** experiments.
- One experiment (preferably the first) must be done comprehensively, with the results being reported in a **paper** whose style resembles that of a 5-7 page physics publication (see the AIP Style Manual) and which is typeset using LaTeX (a document template and instructions will be provided). This experiment, to which the student is to devote three to four weeks, should include a novel extension (novel to Lawrence) developed by the student. The paper should include references to primary literature and show evidence that the student has done the necessary background reading to place his or her experiment in its proper context in the field of physics.
- A second experiment, to which the student is to devote two or three weeks, should also be performed comprehensively (but need not involve a novel extension). The student will present a formal, **oral presentation** on this experiment, patterned after talks delivered at national physics meetings. The length of the talk is strictly limited to twenty-five minutes, followed by five to ten minutes of questions from the class and instructor. The presenter should use **PowerPoint** or equivalent presentation software. She or he should explain the crux of the experiment, present data, and summarize the results.
- Two additional experiments, performed less ambitiously (one to two weeks each), are intended to broaden student exposure to important modern physics topics and instrumentation, and may be undertaken in collaboration with a classmate.
- The four experiments performed by the student must include at least one magnetic or optical resonance experiment (group I below) and at least one nuclear physics experiment (group II below).

I. Magnetic or Optical Resonance

1. Magnetic resonance in optically pumped rubidium
2. Quantum beats via time-resolved laser spectroscopy
3. Saturated absorption laser spectroscopy
4. Optogalvanic laser spectroscopy

II. Nuclear Physics

1. Compton scattering
2. Mössbauer spectroscopy
3. Alpha spectroscopy
4. Gamma-gamma correlation
5. Time-of-flight of relativistic muons

III. Solid State Physics and Miscellaneous

1. Optical Faraday effect in solids
2. Second harmonic generation
3. Laser basics: spectra, power, polarization, divergence, stabilization
4. Holography
5. Hall Effect in thin films
6. High Tc superconductivity and SQuIDs
7. Scanning-tunneling microscopy
8. Child’s law and automated control of experiments using LabVIEW

Notebook:

Activity in this course must be documented ***comprehensively, neatly, and immediately*** in a National 43-648 notebook. **Daily entries** should record your progress, explanations, references, and so forth. For each experiment, the notebook should include (1) a statement of the primary and secondary objectives of the experiment, (2) a complete record of your activities, (3) diagrams and narrative describing the experiment (in enough detail to permit reconstruction of the experiment), (4) data tables, graphs, and/or references to data files, (5) uncertainty considerations, and (6) conclusions.

Dialogues:

Students in this course must have two “informal dialogues”. Thirty to sixty minute dialogues, conducted as if the instructor were a visiting physicist, require clear and concise explanations of the crux of the experiments, recent progress, etc. Students should schedule dialogues only when they understand the essence of an experiment and only when prepared to answer authoritatively obvious questions; notes are not allowed.

Presentation of PRL Articles:

Each student must select an article from a recent (within the last five years) issue of Physical Review Letters and make a 10-minute presentation on it. These presentations should serve to explain the main results reported in the letter. The selected article must focus on *experimental* results as opposed to theoretical or computational results. Physical Review Letters is the premier (American) physics journal where the most significant and recent results are reported in short articles (i.e. "letters"). Presentations will be scheduled in weeks 2 and 3 (see below).

Reading and Discussion:

There will be a regular 45-minute discussion of reading from *Experiments in Modern Physics,* by Melissinos and Napolitano (hereafter referred to as M&N). In some cases a pair of students will be the assigned as discussion leaders. In other cases, the instructors will lead discussion and/or provide short lectures in important topics from the reading. The instructors will advise discussion leaders as to the sections of the reading that are to be emphasized. All students should come to these discussions having read the assigned sections and prepared to ask questions and respond to questions from his or her classmates. Guidelines for the leading of and participation in discussion will be distributed.

Colloquium Attendance:

Each student must attend at least three colloquia during the term. For each colloquium attended the student must prepare a half to one-page summary of the talk. Physics colloquia are preferred but Chemistry, Biology, Geology, and Science Hall Colloquia attendance will be accepted in satisfaction of this requirement. The purpose of this requirement is for students to observe scientific presentations in order to improve their own oral presentation skills. The student should pay attention not only to the scientific content of each talk, but also the organization and style of presentation.

Oral Communication:

This course is designated as "speaking intensive" and satisfies the corresponding general education requirement. Effective oral communication is a crucial skill for the practicing physicist. In this course, students' oral communication skills will be improved and evaluated as part of the following required elements of the course: (1) presentation of a Physical Review Letter, (2) a formal scientific presentation, (3) two informal dialogue sessions, and (4) the leading and participating in discussion of reading assignments. Required colloquium attendance serves to provide examples of scientific presentations whether good, bad or mediocre.

Course Schedule

Week 1 (1/4, 1/6, 1/8)

- MONDAY: Choose primary experiment and make tentative choice of the second. Begin reading background material on first experiment. Get familiar with hardware for first experiment.
- WEDNESDAY: Read and discuss (1) the page on Radiation Safety Considerations (attached to this syllabus), (2) the catalog of radioactive sources (attached to this syllabus), (3) Appendix D from Mellisinos (Radioactivity and Radiation Safety, pp.485-488), (4) Appendix C from Mellisinos (Laser Safety, pp.483-484) and (5) Questions and Answers on Eye Safety with Laser Systems (attached to this syllabus). View laser safety video. Begin work on first experiment in earnest.
- FRIDAY: Physics journals and library databases. We will meet in the CPL to discuss physics journals and electronic databases for tracking down physics articles. **Make interlibrary loan requests for first experiment by the end of the week 1!** Continue work on first experiment.

Week 2 (1/11, 1/13, 1/15)

- MONDAY: Discuss M&N Chapters 1&2 (*Experiments on Quantization* and *Electrons in Solids*). Continue work on first experiment.
- WEDNESDAY: Read sections 1.1-1.2 of *Building Scientific Apparatus* (pp. 1-19, Tools and Shop Processes; Materials). First machine shop session. Continue work on first experiment.
- FRIDAY: Skim section 1.4 of *Building Scientific Apparatus* (pp. 28-37, Mechanical Drawing). Second machine shop session. Continue work on first experiment.

Week 3 (*1/18*, 1/20, 1/22)

- MONDAY: MLK Day. No class
- WEDNESDAY: **PRL presentations**. Continue work on first experiment
- FRIDAY: **PRL presentations** Continue work on first experiment.

Week 4 (1/25, 1/27, 1/29)

- MONDAY: Discuss M&N Chapter 3&4 (*Electronics and Data Acquisition* and *Lasers*). Continue work on first experiment.
- WEDNESDAY: **First dialogue**. Continue work on first experiment.
- FRIDAY: Wrap up first experiment. **Notebooks are due at completion of first experiment**. Begin drafting paper. Read sections I and II (pp. 1-11) of the *AIP Style Manual*. Skim the rest of this document as needed while you write your paper. Discuss physics literature.

Week 5 (2/1, 2/3, 2/5)

- MONDAY: Discuss M&N chapter 5 (*Optics Experiments).* Begin work on second experiment.
- WEDNESDAY: Continue work on second experiment.
- FRIDAY**:** Continue work on second experiment.

Week 6 (2/8, 2/10, *2/12*)

- MONDAY: Skim and discuss section 1.3 of *Building Scientific Apparatus* (pp. 19-28, Joining materials). Continue work on second experiment. **First draft of paper due**
- WEDNESDAY: Discuss M&N chapter 6 (*High-Resolution spectroscopy*). Continue work on second experiment.
- FRIDAY: Midterm Reading Period. No Class.

Week 7 (2/15, 2/17, 2/19)

- MONDAY: Discuss M&N chapter 7 (*Magnetic Resonance Experiments*). Continue work on second experiment.
- WEDNESDAY: Wrap up work on second experiment. **Notebooks are due at completion of second experiment.** Begin preparing oral presentations.
- FRIDAY: Begin work on third experiment.

Week 8 (2/22, 2/24, 2/26)

- MONDAY: Discuss M&N chapter 8 (*Particle Detectors and Radioactive Decay*). **Final draft of paper due.** Continue work on third experiment.
- WEDNESDAY: Continue work on third experiment.
- FRIDAY: Continue work on third experiment.

Week 9 (3/1, 3/3, 3/5)

- MONDAY: Discuss M&N chapters 9&10 (*Scattering and Coincidence Experiments* and *Elements from the Theory of Statistics*). Wrap up work on third experiment. Rehearse oral presentations
- WEDNESDAY: Begin work on fourth experiment.
- FRIDAY: Continue work on fourth experiment

Week 10 (3/8, 3/10, 3/12)

- MONDAY: **Oral Presentations**.
- WEDNESDAY: **Oral Presentations**.
- FRIDAY: Wrap up fourth experiment. **Second Dialog. Notebooks are due TODAY**.

MÖSSBAUER EXPERIMENT

Objectives: To employ the Mössbauer effect to investigate (1) the structure of the 14.4 Kev emission line emitted by ^{57}Fe nuclei imbedded in a Cu matrix, (2) the lower limit of the lifetime of the 14.4 Kev excited state of ^{57}Fe using an isotopically-enriched stainless steel absorber, (3) the comparative widths of the absorption lines of ^{57}Fe imbedded in $K_4Fe(CN)_6 \cdot 3H_20$ and 310 stainless steel, (4) the isomer shift between ^{57}Fe lines for 310 stainless steel and other absorbers, (5) the hyperfine structure of ^{57}Fe in natural iron, and (6) the Mossbauer spectra of ^{57}Fe imbedded in other materials.

References: Melissinos, *Experiments in Modern Physics*
Mössbauer Effect, Selected Reprints
Frauenfelder, *The Mössbauer Effect*

Procedure: Using the Austin Science linear drive and controller, a Reuter-Stokes proportional detector, a chain of NIM instrumentation (preamplifier, amplifier, single-channel analyzer, Canberra Genie-2000 MCS, and high voltage source), observe the Mössbauer spectrum of ^{57}Fe in type 310 stainless steel (use the 92% enriched stainless foil). Using an MCA, develop a systematic procedure to choose SCA discriminator settings that maximize the signal-to-background ratio of the absorption signal. Then observe the absorption of ^{57}Fe in *natural iron* (again using a 92% enriched sample foil). As an extension, you might investigate the Mössbauer spectrum of other iron-containing compounds and/or minerals such as garnets, biotite mica, etc.

ELECTRON PARAMAGNETIC RESONANCE

Objectives: To investiage electron paramagnetic resonance (EPR) in one or more materials to reinforce one's understanding of (1) the Zeeman effect, spin angular momentum, spin flipping, perturbative effects, Bloch equations, and crystal field concepts, (2) the use of microwave techniques and microwave components at X-band frequencies, (3) the use of ac techniques (in this case magnetic field modulation) for signal display/enhancement and perhaps phase-sensitive detection (using a lock-in amplifier), and (4) the measurement of g-values of the semi-free electrons in the radicals DPPH, Cr-doped Mg0, and other samples.

References: Ingram, *Free Radicals*
Melissinos, *Experiments in Modern Physics*
NMR & EPR, Selected Reprints
Pake, *Paramagnetic Resonance*

Procedure: Using first a klystron, attenuator, magic-T, slow-wave structure or cavity, crystal detectors and a frequency counter, observe EPR signals in DPPH and carbazyl. Then use a lock-in amplifier to improve the sensitivity of your EPR spectrometer. Vary the modulation amplitude and frequency, power level, etc. to investigate the signal dependence (or lack thereof) on these parameters. Consider locking the klystron to the cavity or using NMR to determine the magnetic field. Then shift to the Bruker EPR spectrometer, which provides much greater sensitivity and control. Attempt to observe EPR of in various other materials. Measure the g-values to the highest possible precision and accuracy.

TIME-RESOLVED LASER SPECTROSCOPY: QUANTUM BEATS

Reference: Study and follow the detailed set of instructions in the red binder and Brandenberger's discussion of quantum beats in his *Report*. This experiment employs an N_2-pulsed laser which pumps a Littman-Metcalf tunable dye laser. The main purpose of this experiment is to acquaint the student with fluorescence spectroscopy, the classical and quantum interpretations of quantum beats, and a pulsed tunable laser system.

OPTICAL PUMPING OF RUBIDIUM

Objectives: To investigate various facets of optical pumping in rubidium by (1) observing the disorientation of optically pumped/oriented Rb vapor due to radio-frequency magnetic resonance and/or rapid passage through zero magnetic field, (2) observing the linear and quadratic Zeeman effects in Rb, (3) determining the Lande g-factors and confirming the values of nuclear spin for ^{85}Rb and ^{87}Rb, (4) studying the transient phenomena when the rf field is amplitude modulated at a fixed value of magnetic field, (5) observing the magnetic resonance linewidth as a function of rf field strength and light intensity, (6) observing multi-quantum rf resonances, and (7) determining the disorientation relaxation time and pumping-up times.

References: B. Smith, Honors Thesis, Lawrence University (1969)
De Zafra, Am. J. Phys. 28, 646 (1960)
Benumof, " " " 33, 151 (1965)
Nagel & Haworth, Am. J. Phys. 34, 553 (1966)
Happer, Rev. Mod. Phys. 44, 169 (1972)
Masers and Optical Pumping, Selected Reprints
Bernheim, *Optical Pumping: An Introduction*

Procedure: Following the set of instructions in the red binder, recreate the various optical pumping lineshapes displayed there. Let this experiment reinforce physically various topics that you encountered in Physics 31.

COMPTON EFFECT EXPERIMENT

Objectives: To investigate Compton scattering to (1) learn scintillation spectroscopy and the use of a multichannel analyzer, (2) verify the predicted shift of the Compton peaks with angle, (3) infer the rest mass m_o of the scattering electron, (4) attempt to verify the Klein-Nishina formula, and (5) investigate the energy shift of the peak of the electron recoil spectrum.

References: Shankland, *Scientific Papers of A. H. Compton* (esp. articles on pp. 82 and 414)
Melissinos, *Experiments in Modern Physics*
Semat, *Introduction to Atomic and Nuclear Physics*
Siegbahn, *Alpha, Beta, and Gamma-Ray Spectroscopy*
Richtmeyer, Kennard, and Cooper, *Introduction to Modern Physics*

Procedure: In performing this experiment, concentrate first on the *shift* of the 0.662 KeV ^{137}Cs photopeak as a function of scattering angle θ. Use a 1" diameter Al rod as the scattering target, a 2" diam NaI(Th) scintillation detector composed of a NaI crystal and photomutiplier, and a PC-based Genie-2000 multichannel analyzer. Then repeat the experiment focusing upon the *intensity* of the scattering peak as a function of θ to test the Klein-Nishina formula. Next investigate the Compton scattering as a function of target Z. Include corrections for MCA calibration, zeroing, detector efficiency, target geometry, beam profile, etc. You might attempt to reconfigure the experiment by using coincidence techniques.

OPTOGALVANIC LASER SPECTROSCOPY

Objectives: To exploit the optogalvanic effect in a discharge to investigate (1) the energy levels and populational dynamics of atomic neon and argon, (2) the use of an argon-pumped tunable dye laser for laser spectroscopy, and (3) the use of ac techniques and lock-in detection.

Procedure: Look at Lawler's review article and past student papers in the red binder.

NUCLEAR MAGNETIC RESONANCE EXPERIMENT

Objectives: To investigate nuclear magnetic resonance in liquids to (1) reinforce one's understanding of the nuclear Zeeman effect, angular momentum, spin precession, spin flipping, perturbative effects, Bloch equations, etc., (2) become acquainted with the operation and performance of a marginal oscillator, (3) gain appreciation of ac techniques (in this case magnetic field modulation) and signal enhancement through signal averaging and/or lock-in amplification, (4) become adept at measuring magnetic fields to high precision via NMR, (5) attempt to understand the transient effects associated with rapid passage through the resonance condition, and (6) investigate saturation effects and relaxation times.

References: Melissinos, *Experiments in Modern Physics*
Andrew, *Nuclear Magnetic Resonance*
Abragam, *The Principles of Nuclear Magnetism*
NMR and EPR, Selected Reprints
Brandenberger, *Laboratory Computing*

Procedure: Use the permanent magnet setup to observe the rapid passage NMR signal. Investigate the effects of paramagnetic doping on the relaxation times.

ALPHA SPECTROSCOPY

Objectives: To investigate alpha-particle emission via charged particle spectroscopy using a passivated implanted planar silicon (PIPS) detector in a light-tight evacuated chamber. The aims of this experiment are (1) to become acquainted with the PIPS detector, (2) to perform charged-particle spectroscopy with a multichannel analyzer, (3) to study the natural radioactive decay chains, and (4) to infer the spectral effects of coverings laid over alpha sources.

References: Melissinos, *Experiments in Modern Physics*
Canberra Laboratory Manual

Procedure: Carefully read and diligently observe the precautions regarding the application of vacuum, light, and increasing voltages to the PIPS detector. For an initial spectrum and calibration purposes, use the ^{241}Am source; then move on to the alpha sources removed from smoke detectors and the new multi-line alpha source. *Do not touch the gold-plated top surface of the latter.*

SECOND HARMONIC GENERATION EXPERIMENT

Objectives: To investiage the non-linear optical effect known as second harmonic generation, by which process light of a given frequency is "doubled" to produce light of exactly twice the frequency (or one-half the wavelength).

References: Bloembergen, *Non-Linear Optics*
Giordmaine, *"The Interaction of Light with Light"*
Franken and Ward, *"Optical Harmonics and Nonlinear Phenomena"*

Procedure: Use the Coherent 599 cw dye laser for excitation, a KDP crystal for doubling, and a solar-blind photomultiplier for separation of the second harmonic from the fundamental. Investigate polarization effects and the dependence of the SHG conversion efficiency on angle tuning and laser focussing.

SATURATED ABSORPTION LASER SPECTROSCOPY

Objectives: To use saturated absorption laser spectroscopy to investigate (1) the hyperfine structure of the ground and first excited states of ^{85}Rb and ^{87}Rb, (2) Doppler-free spectroscopy, (3) the isotope shift of the energy levels of Rb, (4) polarization and power-broadening effects in saturated absorption, and (5) the use of diode lasers in atomic spectroscopy.

Procedure: Follow the detailed set of instructions in the red binder and study Brandenberger's *Report* for a discussion of saturated absorption and the experimental layout. Look at Camparo's review of diode lasers and past student papers on this experiment.

FARADAY EFFECT EXPERIMENT

Objectives: To investigate the Faraday effect whereby the plane of polarization of a beam of linearly polarized light rotates as the beam propagates through some material in the direction of a large, externally applied magnetic field. The aim here is to measure Verdet constants, which characterize the strength of the Faraday effect in different materials at different wavelengths.

References: Jenkins and White, *Fundamentals of Optics*
Hecht, *Optics*

Procedure: Following DeMets and McDonough and other past students, use the cubic samples of heavy and light flint glass, polaroid polarizers, a 4" electromagnet, and HeNe lasers that lase at different wavelengths. Other materials should then be investigated at different wavelengths.

LASER BASICS EXPERIMENT

Objectives: To investigate laser operation and behavior with particular emphasis upon (1) discharge and cavity characteristics, (2) cavity adjustment and alignment, (3) power optimization, (4) output beam profile and polarization, (5) use of a spectrum analyzer to explore the stability and longitudinal and transverse mode relationships, (6) use of piezo elements and external circuitry to stablize a laser, (7) techniques for achieving single-mode operation, (8) introduction of intra-cavity elements, and (9) use of an external plane-parallel Fabry-Perot cavity.

References: O'Shea and Peckham, *Lasers: Selected Reprints*
O'Shea, Callen & Rhodes, *Introduction to Lasers and Their Applications*
Lasers and Light (Scientific American Reprints)
Brandenberger, *Proceedings* and *Report*

Procedure: After a preliminary reading of some of the references, investigate the starting, operation, and adjusting of the lasers, especially for maximization of power. Exercise great care and respect for your eyes (and those of others), the spectrum analyzer, and laser power meters. Look at the mode profiles and ascertain how you can favor one mode at the expense of others. Move on to mode analysis using the spectrum analyzer; try pulling the laser with the piezo elements. From here on the experiment is open-ended; many things are possible.

SUPERCONDUCTIVITY

Reference: Look at the Conductus manual for an introduction to various experiments that can be performed with Mr. Squid.

GAMMA-GAMMA CORRELATION EXPERIMENT

Objectives: To investigate the correlation of gammas emitted by electron-positron annihilation and/or the rapid two-photon cascade decay of ^{60}Co. A practical objective of this experiment is to become familiar with scintillation spectroscopy, NIM instrumentation, and coincidence techniques.

References: Melissinos, *Experiments in Modern Physics*
Seaman, *Canberra Laboratory Manual*
Siegbahn, *Alpha, Beta, and Gamma-Ray Spectroscopy*

Procedure: Use the needle-shaped ^{22}Na positron source to set up the standard gamma-gamma correlation experiment. Use this arrangement to become familiar with the SCAs and coincidence module; use a Canberra MCA to set the discriminator windows. Take enough data to verify the strong directional correlation of the annihilation gammas. Think about the idealized "lineshape" for the angular distribution of these gammas assuming a *line* source and narrow *rectangular* apertures in front of the detectors. Think about the effect that an extended source would have on this lineshape. Think about the lineshape effects due to decaying positronium not initially *at rest* in the lab. Use the same apparatus but ^{60}Co to pursue a more difficult gamma-gamma correlation.

X-RAY DIFFRACTION EXPERIMENT

Objectives: To learn x-ray diffraction methods to examine the structure and correlations in solids and fluids. Use x-rays to study crystalline (Al) and amorphous (glass) materials.

References: Preston and Dietz, *The Art of Experimental Physics,* p. 180-192
Ashcroft and Mermin, *Solid State Physics*

Procedure: After reading appropriate sections of the recommended references, determine what one should expect when x-rays are scattered from a target of polycrystalline aluminum. After making a sketch of the diffraction process on the Siemens x-ray diffractometer, collect a diffraction pattern from an aluminum foil sample and compare with your prediction. Follow this measurement with diffraction from a piece of glass; develop a qualitative interpretation of this pattern. Extensions may include looking at liquid crystal phases and transitions between them.

TIME OF FLIGHT OF RELATIVISTIC MUONS

Objectives: To measure the time of flight of relativistic muons (generated in the upper atmosphere by cosmic rays) as they traverse the separation between two plastic scintillator paddles, to become familiar with fast NIM electronics and a time-to-amplitude converter (TAC), and to confirm indirectly Lorentz contraction or time dilation.

References: MIT Junior Laboratory Instruction Set for this experiment
Canberra NIM Manual

Procedure: Examine the pulse height spectrum of the scintillation pulses emitted by the paddle/PMT detectors. Then connect the paddle detectors to the Canberra constant fraction discriminators, and connect the CFD outputs to the TAC module. Dump the output of the TAC on a Canberra MCA. Note how cable lengths and paddle separations affect the observed time interval between the start and stop pulses. Proceed to measure times-of-flight and hence velocities of relativistic muons raining down on Y-56.

RADIATION SAFETY CONSIDERATIONS

1. A "**Curie**", abbreviated Ci, is a measure of the *activity* of a radioactive sample in terms of nuclear disintegrations per sec; $1\text{Ci} = 3.7 \cdot 10^{10}$ disintegrations/sec. The following is true so long as the sources of radiation remain *outside* the human body: **Submicrocurie** sources are very weak and relatively harmless; **microcurie** sources are weak and pose little danger. **Millicurie** sources in close proximity to a human can deliver unacceptable doses of radiation and must be treated carefully. **Multimillicurie** sources are dangerous. **Curie** sources should be handled by pros.

2. A "**Becquerel**" is a much smaller yardstick of activity: 1 Bq = 1 disintegration/sec.

3. A "**Roentgen**" is an amount of x-ray/gamma **exposure**: 1 R is that amount of x-ray or gamma exposure that generates $1.6 \cdot 10^{12}$ ion pairs/gm in dry air, which amounts to roughly 10^9 ions in one cm^3 of air. This exposure or amount of ionization requires about 78 ergs/gm. An exposure of 1R is large and totally unacceptable especially if absorbed in a short interval of time or by most of the grams in a living target.

4. A "**rad**" represents an **absorbed dose** of **any** type of radiation, where the absorber is usually imagined to be living tissue. The rad is defined in terms of *absorbed energy/mass* of absorber: **1 rad = 100 ergs/gm** of absorbed energy (absorbed via ionization). The rad is more useful than the Roentgen because it applies to all types of radiation. For x-rays and gammas in the 100Kev to 3Mev region, an exposure of 1 R produces an absorbed dose of roughly 1 rad.

5. A "**rem**" is a measure of absorbed radiation defined by the expression

$$\text{dose equivalent (in rem)} = \text{dose (in rad)} \cdot \text{RBE}$$

where the RBE, the "relative biological effectiveness", is 1 for x-ray, gamma, and beta radiation and 10 for protons, fast neutrons, and alphas.

The rem reflects the comparative destructiveness of different types of radiation, and indicates the greater potential destructive power of protons, fast neutrons, and alphas once they have intruded inside the body. The **rate** of doseage is also important; a given total dose delivered over a long time is much more acceptable than the same dose delivered quickly. Dose rate are expressed in units of **rem/hour** or **rem/year**, etc. Here are some useful yardsticks:

Background dose rate: At sea level each gram of our body absorbs about 0.1 rem/year of cosmic-ray or earthen-based radiation. One might view this doseage as inevitable. At 30,000 ft cosmic ray background doseages are substantially higher.

Maximum permissible dose rate for a professional worker in a ***radiation-restricted area:***

1.25 rem/quarter (50x background) for bodily grams of muscle and glands.
7.5 rem/quarter (300x background) for grams of skin.

In ***unrestricted areas***, *the acceptable radiation dose rates* are 2 mrem/hr (200x background) for brief exposures of an hour or so, but less than 100 mrem/week (50x background) for long term continuing exposures.

Catalog of Radioactive Sources; Lawrence University Physics Department
(Revised December, 1999)

I. Alpha Sources

1. ^{241}AMERICIUM ($T_{1/2}$ = 485 yr). Our pure ^{241}Am source (ICN/Tracerlab Type 170) was procured in 1971 with an activity of 4540$\pm$3% alphas/min (2 nCi) emitted into a **hemi**spheric geometry. The radioactive portion of this source was electrodeposited on a 1" diam nickel **disk** held on a 1" x 1/4" cylindrical mount by a cylindrical ring. This source is stored in a Tracerlab box inside the lead-lined chest. Leave the disk on its mount during use.

^{241}Am decays by alpha emission to various excited states of ^{237}Np. Since the ^{241}Am in this source resides on the upper surface of the nickel disk and there is no window, the 5.443 Mev (12.7%), 5.486 Mev (86%) and 5.389 Mev (1.3%) alpha lines are sharp (FWHM of about 20 Kev). The ^{237}Np daughters decay to their ground states by emitting various low-energy gammas, the predominant one being 59.57 Kev. ^{237}Np is relatively stable ($T_{1/2}$ = 10^6 yr) .

Alpha particles are attenuated very effectively by 20 cm of air, a sheet of paper, or the outer layer of human skin. The primary danger associated with alpha sources is ingestion, absorption, or inhalation. The "maximum body burden" of ^{241}Am is 60 nCi, the maximum amount of activity that should be allowed to accumulate in a human. This value is based on the long-established figure of 100 nCi for radium. Although this maximum burden is *30 times the total activity of this sample*, the source should be accorded respect. Since the radioactive surface has no cover, users should not *touch the disk.* Wash your hands after handling this source or any object to which it makes contact. A second concern involves the 59.57 Kev gammas, but this risk is insignificant because of the low activity. The activity of this source is so low so as to exempt it from wipe testing. The Department also uses ^{241}Am sources removed from smoke detectors.

2. ^{210}POLONIUM ($T_{1/2}$ = 138 day). The Department's ^{210}Po source (ICN type R-17(c)) was procured in 1959 with an original activity of 10 nCi. However, as of March 1980, roughly 55 halflives had elapsed, leaving as of that date, an activity equal to only $(1/2)^{55} = 10^{-14}$ of the original value (10^{-16} µCi)! Since ^{120}Po decays to the stable nuclide ^{206}Pb, this source is dead. This source is stored permanently in Y-51B and gets no wipe tests.

3. ^{239}PLUTONIUM($T_{1/2}$ = 104 yr), ^{244}CURIUM($T_{1/2}$ = 18 yr), and ^{241}AMERICIUM($T_{1/2}$ = 485 yr). We have a new Type #AF composite alpha source containing 10 nCi of each emitter, all covered by a 100 µgm/cm^2 gold layer, delivered by Isotope Products in October, 1995 (catalog type AF-COMP-C-10N). This source was electrodeposited and diffusion bonded onto a platinum clad nickel disk. The gold covering surface is **very delicate and should never be touched or wiped.** This source is used in alpha spectroscopy; its major emission peaks fall at 5.1302MeV (Pu-239), 5.4629 MeV(Am-241), and 5.7824 MeV(Cm-244).

II. Pure Gamma Sources

1. ^{57}COBALT ($T_{1/2}$ = 270 day). The Department has puchased eight ^{57}Co sources:

(a). One NSEC demonstration source procured at an unknown date prior to 1968 with an original activity of 1 mCi. This source is similar to (b) below except that the foil is palladium and there is no plastic mount. Another 1 mCi NEN #599 ^{57}Co source was procured in 1968. This source also resembles (b) below except that the foil is iron and does not have a plastic mount.

(b). One ICN #SN Co-569 ^{57}Co source that was procured in January 1970 with an original activity of 2mCi. ^{57}Co was electrodeposited and diffused into the center portion of a 1/2" diam copper foil which was then covered with a light film of acrylic plastic and mounted on a 1/2" diam x 3 mm thick acrylic source holder. Radiant flux should be taken from the side of the source with the 1/4" diam hole. This source was certified to exhibit a minimal gamma linewidth; four iron absorbers and a lead storage chamber were included in the $220 package.

(c). An Isotope Products Laboratory No. 34090 ^{57}Co source was procured in 1977 with an original activity of 3 mCi. ^{57}Co was deposited (electrodeposited) and diffusion bonded onto a Cu matrix: catalog description is Mos-57-Cu. The active diameter of the source is 0.25 inches; the backing of the source is .001" Cu. The front of the source is covered with an acrylic spray of thickness 100 microgram/cm^2. The source was delivered in a brown wooden box with identification on top. Iron and stainless steel absorbers were delivered with the source; their thicknesses and compositions: stainless steel type 304 by .001 inch thick, and 99.99% pure iron by .001 inch thick. The source is mounted in a 5/8" diamter acrylic disk. Cost: $290.

(d). Another Isotope Products Laboratory ^{57}Co source, designated MOS-57-Cu, had an activity of 3 mCi when delivered in April 1980. Otherwise it is identical to (c). It does not require wipe testing because it is an "open" rather than "sealed" source.

(e). Another Isotope Products Lab ^{57}Co source, designated MOS-57-Cu and hence similar to (c) and (d), was procured in October of l989 with an original activity of l mCi. Price: $420. Another 2 mCi IPL ^{57}Co source designated MOS0057 consisting once again of ^{57}Co electrodeposited on a Cu matrix was procured in October 1991. A very similar IPL ^{57}Co MOS-DEMO source of strength 5 mCi was procured 4/16/97; it requires no wipe testing because it is an "open" source.

^{57}Co decays by electron capture to an excited state of ^{57}Fe which relaxes to its ground state by emitting either a single 136.31 Kev gamma (11%) or a 121.94 Kev and 14.39 Kev pair of gammas (89%). The exposure rate for a 5mCi point source of ^{57}Co is about 2.5 mR/h at a distance of 1 m. Since the relative biological effectiveness of gamma radiation is 1, this figure translates into about 2.5 mrem/h for the same source and a human target separated by one meter. This dose rate can be tolerated for roughly 40 h without undue harm. A total exposure of 100 mrem (2.5 mrem/h x 40 h) accumulated over the period of a week or so is deemed acceptable by the NRC. The NRC recommends, however, that students under the age of 18 be exposed to no more than 100 mrem/yr for educational purposes alone.

At a distance of only 1 cm, however, a 5 mCi source is considerably more dangerous because one acquires a given dose 10^4 times faster. At this distance from a 5 mCi source of ^{57}Co, one is exposed to 25 rem/h. A total exposure of 10 rem causes detectable changes in human blood. An exposure of only 1 rem accumulated over the period of an hour, however, produces no detectable physiological effects. Hence the ^{57}Co user can safely handle any of these sources with tweezers for a minute or so without serious risk. When in use, however, radiation signs should be posted and personnel should remain several meters away except for occasional adjustments. The main use of these ^{57}Co sources is ^{57}Fe Mössbauer spectroscopy.

III. Combined Gamma and Beta Sources

1. ^{60}COBALT ($T_{1/2}$ = 5.26 yr). The Department's ^{60}Co source was produced by Amersham in February 1980 with an original activity of 1 mCi. It is designated type CKC.24. The ^{60}Co is located in the cylindrical end of a stainless steel capsule that has a small handle with a hole in it. ^{60}Co decays by beta emission to several excited states of ^{60}Ni; the most probable beta transition (99.5%) has a maximum energy of 319 Kev. The associated excited state of ^{60}Ni decays to its ground state via two gammas (1.17323 Mev and 1.33248 Mev) in rapid succession (10^{-12} sec).

The gamma exposure rate for 1 mCi of ^{60}Co is about 1 mR/h at a distance of 1 m. Hence the safety precautions described above for 2 mCi of ^{57}Co apply to this 1 mCi source of ^{60}Co. One must consider, however, in addition, the beta emission. The 319 Kev betas have a maximum range of about 75 cm in air, 0.6 mm in soft human tissue, or 0.05 mm in lead. Hence we conclude that the betas emitted by ^{60}Co need be of little concern. When handling this source, most of the betas will be stopped in the dead (cornified) layer of the skin, and negligible amounts will reach the blood stream or vital organs. Handling, nevertheless, should be minimized. The main uses of this source are gamma-gamma correlation and gamma spectroscopy experiments. This source should be wipe tested every six months.

2. ^{137}CESIUM ($T_{1/2}$ = 30 yr). The Department's current ^{137}Cs source was produced by Amersham in February 1980 with an original activity of 1 mCi. It is designated as type CDC.701. The capsule is cylindrical in shape and mounted semi-permanently in a 4" x 8" x 2" lead brick collimator. ^{137}Cs decays in two ways: (1) by beta decay (maximum beta energy of 514 Kev) to an excited state of ^{137}Ba, which decays to its ground state by emitting a 661.6 Kev gamma (93.5%), or (2) directly to the ground state of ^{137}Ba with a maximum beta energy of 1.176 Mev (6.5%). The 1.176 Mev {514 KeV} betas have ranges of 200 cm {100 cm} in air, 3 mm {1.5 mm} in soft human tissue, or 0.2 mm {0.1 mm} in lead. Hence the beta emission from ^{137}Cs is more dangerous than that of ^{60}Co discussed above. The gamma emission from this source is less dangerous than that of the ^{60}Co source, because there are only half as many gammas and the gammas are only half as energetic. Thus the precautions observed for using the 1 mCi ^{60}Co should be more than adquate for protecting the user from gamma exposure by this particular ^{137}Cs source. The primary applications for this source are Compton scattering and gamma and beta spectroscopy; this source should be removed and wipe tested every six months.

IV. Positron and Gamma Sources

1. ^{22}SODIUM ($T_{1/2}$ = 2.6 yr). The Department's original ^{22}Na source was a sample of NaCl deposited inside a silver-painted 3 cm diam x 4 mm thick lucite disk mounted in a 3" x 1-1/2" acrylic holder. Purchased from Amersham/Searle in April 1972 with an original activity of 100 μCi, it is now retired from service. The Department procured another ^{22}Na source of 100 μCi in 2/1/84. This source is mounted in a 5/8" diameter, 5" long plastic rod, and was supplied by Isotope Products Laboratory. This source was wipe tested before shipment, and should be wipe tested every 6 months. A third ^{22}Na source follows the same description except that it was 200 μCi as of delivery in 10/89; the price was $450. This source needs wipe testing every six months. A fourth ^{22}Na source, this time as a very thin kapton wafer of diam 1/2" and 3 mm active area, was purchased in October 1991. The radioactive Na is in the form of NaCl crystals. One must be very careful not to press against the kapton and puncture the seal; no tools nor sharp instruments

should be used near this source. On 4/16/97, the Department acquired another and much safer 1 mCi ^{22}Na source sealed in a 5 cm long stainless needle. The active area is 1 cm long and indicated by green paint along the needle.

^{22}Na decays to an excited state of ^{22}Ne by two processes — either positron emission (90%) or electron capture (10%). The maximum energy of the positron is 545 Kev. The ^{22}Ne daughter decays quickly (10^{-12} sec) to its ground state with the emission of a 1.2746 Mev gamma. The positron forms positronium and decays rather quickly into a pair of 0.511 Mev coincident gammas. These 100 or 200μCi samples of ^{22}Na should be accorded the same care and respect as that suggested for the ^{60}Co source. The primary use is gamma-gamma coincidence work.

Questions and Answers on Eye Safety with Laser Systems

Question: At what power thresholds can a laser cause damage to the retina?

Answer: Unfortunately, there is no specific power level that one can quote and assert that a laser of this particular power cannot cause retinal damage. The degree of risk or damage depends on wavelength, exposure duration, whether the laser is continuous wave or pulsed, and the target biological organ. Maximum permissible exposures (MPEs) are based on all four factors. Laser safety is concerned not so much with what power will cause damage to the eye or skin but with the safety precautions that can be used to prevent overexposures.

The standard approach is to categorize lasers into four classes — Class 1 through Class 4. Once you know which class a laser falls in, then you know the safety precautions that should be taken. The higher the class, the more hazardous and more important the precautions.

Question: What are the definitions of these classes?

Answer: The definitions depend upon how a laser may damage the eye given a specific set of exposure conditions. A Class 1 laser system is considered essentially eye-safe. If you were to stare at a Class 1 continuous wave laser, regardless of wavelength, for eight hours, you would not receive eye damage. This MPE level of eight hours is set about a factor of 10 below a level which causes a visual lesion 50% of the time.

Question: So the time frame is eight hours then?

Answer: Yes, for a Class 1 continuous-wave laser, but Class 1 lasers are very low power.

Question: What is an example, say, for a HeNe laser? What is the power threshold of Class 1?

Answer: Some helium-neon lasers are Class 1, but most HeNe lasers fall in a higher class. Most lasers that are considered Class 1 contain higher-powered lasers, but the laser in these cases is completely enclosed so that exposure to the beam is not possible except by the defeat of certain safety features built directly into the system. An example would be the laser in a laser printer.

For HeNe laser systems, you still need to be able to stare at a Class 1 laser for eight hours with no damage. For a continuous-wave visible system such as a HeNe, the power must be less than 0.4 microwatt according to a Food and Drug Administration (FDA) standard, but there is also a wavelength correction factor for wavelengths greater than 550 nm. The laser classes are divided by Accessible Emission Limits (AEL), i.e. power thresholds, and these are dependent upon whether the laser is cw or pulsed, the wavelength and duration.

The AEL thresholds for continuous wave lasers which have a potential exposure duration greater or equal to 0.25 sec are as follows: all Class 2 lasers must emit visible beams. If a laser's output is *invisible* and the laser emits above the Class 1 AEL threshold of 0.4 microwatt, the laser automatically goes into Class 3. We assume for Class 2 lasers that a person's eye will be exposed for no more than a quarter of a second, which is the aversion (blink) response time. If one looks at a bright light source, one automatically limits his or her exposure to that source by turning away or blinking. But if one can't "see" the source, obvioiusly there will be no safety through aversion or blinking. So a Class 2 laser system must be visible.

Question: What is the power level for Class 2?

Answer: For a cw laser system such as a HeNe, it must be greater than the Class 1, but no greater than 1 mW. A laser beam of 1 mW or less is still weak. Many HeNe lasers, in fact most of the HeNe's at Lawrence, have powers of 3 - 10 mW. So they fail to fall in Class 2.

Question: What about Class 3?

Answer: Class 3 laser systems are medium-power laser systems. They can be visible, ultraviolet, or infrared. For a continuous wave laser system, a 0.25 sec exposure duration for visible systems and 10 sec exposure duration for nonvisible systems is assumed. The 10 sec exposure duration is assumed since the laser is invisible. It is assumed that within 10 sec of exposure the person will become aware of the laser light and will move, thus limiting the exposure time. Also, normal head and eye movement tends to limit exposure to the same area of the retina to less than 10 sec.

Question: And what are the Class 3 lower and upper threshold power levels?

Answer: Greater than 1 mW but less than 500 mW or 0.5 W. There is also a wavelength correction factor to be taken into account.

Question: And how about Class 4?

Answer: Class 4 continuous wave lasers are those that emit more than 0.5 watts. The problem with a Class 4 laser system is that it can be hazardous not only for viewing the direct beam, but it may also be hazardous to view an accidental or even diffuse reflection. These lasers are also capable of producing fire and skin damage, especially when they are focussed.

Question: Are there specific types of eye safety glasses that will make a laser light more diffuse?

Answer: The most common types of laser eye protection use either absorption or reflection type filters. In an absorption filter, enough of the laser energy is absorbed so that what is allowed to pass through is below the MPE, and therefore, safe to view. The material will either be glass or plastic with an organic or inorganic dye added to it. That dye is sensitive to a specific wavelength or band of wavelengths.

In reflection filters, material commonly used is a dielectric coating. The coating is actually laid down in layers about a quarter of a wavelength thick. The cumulative effect of the reflections can be made to constitute a nearly complete or a nearly zero reflection as a result of interference. The problem is the angular dependency of this film. You need to know the angle which the laser light is incident upon the filter. Light that is incident upon the filter from any angle off normal will travel a slightly longer path. This distance between layers may no longer be a quarter of a wavelength apart from this light and the filter may allow that wavelength to pass through. There is also the problem of applying this coating to a curved surface, which is necessary for eye glasses to avoid a prismatic effect, and still maintain the quarter wavelength measurement.