

PHY 445/515: Course Notes

(rev. 9/1/07)

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Introduction

The information in these notes is a collection of more detailed instructions and suggestions for doing the various activities that comprise this course. The definitive course rules and procedures are contained in the Syllabus. You are responsible for being thoroughly familiar with both of these documents. You should read them several times during the semester and then reread various sections as the need arises. For example, if you are about to start an experiment using a radioactive source, reread the radiation safety section, reread the section on writing reports before you begin your first report, etc. You may expect to be asked about any material relevant to a given experiment in your pre-experiment discussion.

Experimental Procedures

There are two equally important challenges to doing an experiment: The first is to develop procedures and techniques which, given the equipment, allow you to get the best possible results. The second is to convince those who look at your results that they mean what you claim; otherwise all your work is wasted.

Listed below are some of the steps which are crucial to a successful experiment and report. The list is not strictly chronological since there is a lot of feedback among the various steps.

- **Understand the physics** that you will be studying. Before you appear in the lab to begin work on an experiment, you should have studied the write-up and some of the references both to familiarize yourself with the physics involved and to see what experimental techniques others used.
- **Understand the equipment** you will be using. When you begin work on an experiment you should meet with one of the staff experts to discuss the equipment, which may not be working exactly as described in the write-up. In general the equipment is complex. If you do not understand how it is supposed to work, and how it is actually working you will almost certainly make errors in your measurements.
- **Decide what you wish to demonstrate**, e.g. that you wish to determine the lifetime of the muon, and decide what is the required accuracy of the measurement techniques to do this. This requires to think beforehand about the errors.
- **Demonstrate that you are not making mistakes** in your measurements. This mainly involves demonstrating a thorough understanding of all aspects of the measurement process as well as developing experimental cross checks wherever possible to demonstrate the validity of your results.
- **Determine the final uncertainty** of your result. This involves knowing the accuracy of your instruments, the statistical uncertainty due to noise of counting, the reproducibility of your results and often an estimate of the residual errors due to your incomplete understanding of the measuring process. You should make every effort to reduce this last item to a negligible level.
- **Data taking:** All the work you do in the lab is to be recorded directly into your lab book as you do it. If it is necessary to make large tables of data (either "by hand" or from a computer printout), one of you can make/take the "master copy". The other can make a photocopy of these data, so it is not necessary for both partners to copy large tables of data. This laboratory log will certainly (and should) contain all the mistakes you are making as you are learning. Simply note them and continue. These mistakes will not be held against you; rather, they are a record of how you "found your way" through the experiment. This log should be a fully literate record, readable and interpretable by you or somebody else after a long delay. Your daily log should also include block or schematics of apparatus, and all the pot or other settings on the electronics. This way, if you have to continue at the next session you can check that your settings have not been changed! (Another group may be using the equipment on the day(s) that you are not using it.) You should enter comments when changes are made, neatly labeled tables of data taken, estimates of reading errors and other sources of error.
- **Data analysis:** You must analyze your data while you are doing the experiment. This is the only way to spot mistakes and improve your techniques and determine if you are finished, while you can still take corrective action. Make a rough graph

of the data immediately to see if the data make sense. This is the "quick and dirty" analysis that you and your partner are permitted to do together. However, each of you **MUST** do the final analyses of data **SEPARATELY**.

Some experiments require you to be in the lab outside of regular course hours. For these situations the following rules apply:

- You must be signed in on the sheet hanging on the door any time you are in the lab after normal hours.
- You must have staff permission (TA or professor) to be in the lab after hours.
- For safety reasons you may not be in the lab alone.
- After-hours work is only an add-on to the regular class attendance. You cannot substitute after-hours attendance for the regular class hours.

How to Keep an Good Log Book

Remember: The preparation, experimental work, rough "in-lab" data analysis is/may be done with a partner, but record the data in your own log book. All the final analysis and the writeup must be done independently.

At least **Two** notebooks are essential. One notebook, carrying a complete log and report, will be handed in for grading, while you are using the other notebook for a new experiment.

The log book must be bound (cloth bound or spiral) and each page must be numbered. You may want to select a notebook which has graph paper in it. The spiral-bound "Engineering/Science" notebooks with alternate pages graph and lined paper are recommended but not required.

You may start taking notes in your logbook even before the start date, when you are making notes/calculations and preparing for the experiment. The activities, instrument settings in the lab should be recorded so that you (or another reader) are able to reconstruct the events even years after the data were taken. **It is very important to keep track of dates and record the time of day for all data you take and analyses that you do.**

Do not try to erase the records if you made a mistake! Making a mistake will not be held against you; not noticing a mistake will be.

It is a good practice to take notes on one side of the pages and put graphs on the other side. Always do a quick check (graphical or otherwise) of your data as you collect them in the laboratory. Make sure that you are obtaining decent results, not nonsense. Remember that the brain is exceedingly efficient at assimilating and interpreting patterns (i.e. graphs) after millenia of selective evolution. Evolution has not prepared us to digest numerical tables! Even in the age of computers, do not hesitate to graph data by hand,

preferably right after (or during) the time of data collection. Alternatively, enter the data into a spreadsheet program like EXCEL on the spot, and create, print and paste the graph to the logbook. (See the example at the end of this section) Do not wait until some "later time" to find out that your data are worthless.

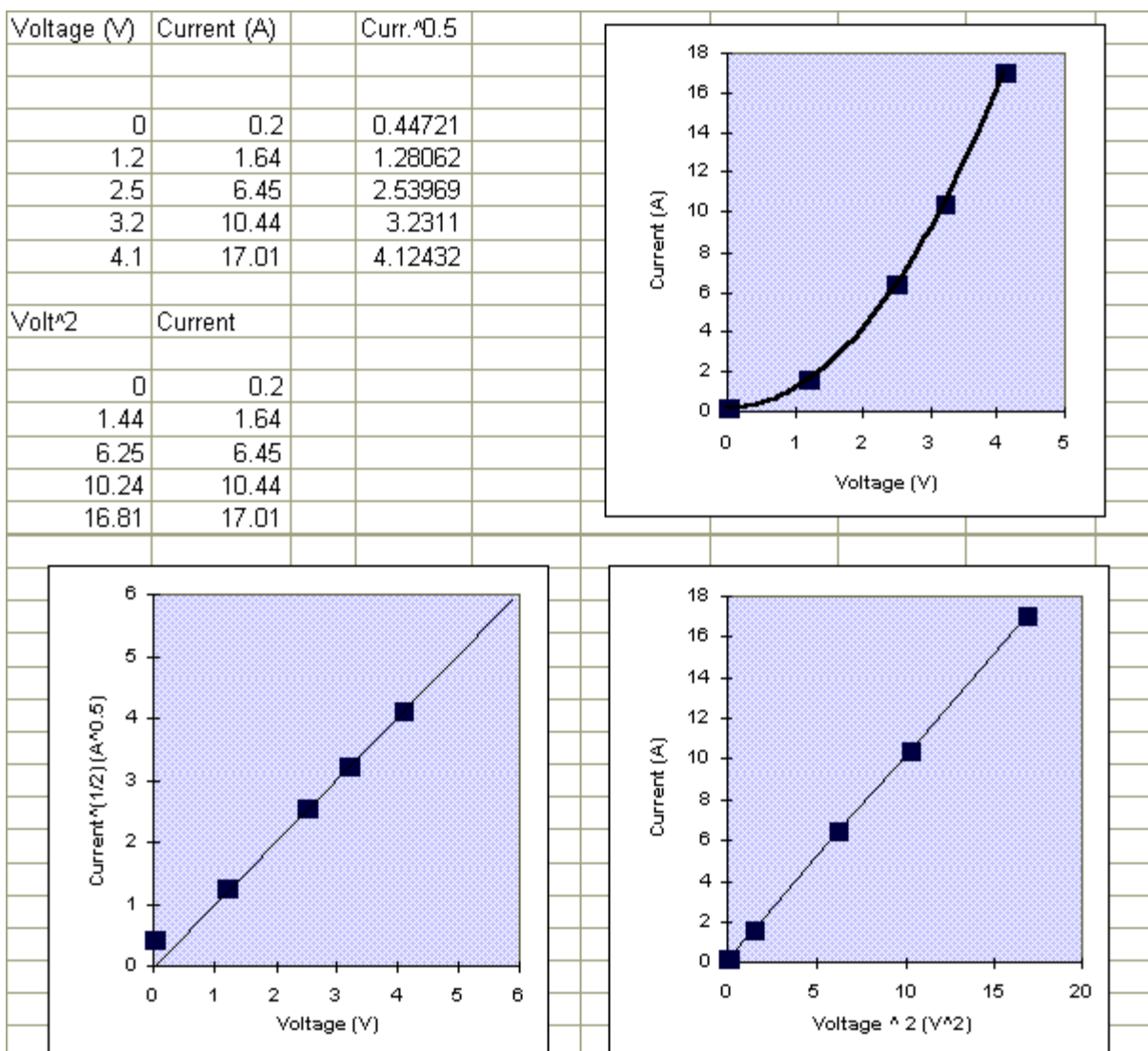
Data taken by using a computer should be recorded in the log book by date/time/filename and the parameters changed between the subsequent data sets. Back up all data/analysis files on a floppy disk that you keep in a safe place. WARNING: Practice safe computing. Viruses have occurred in the lab computers.

Computer printouts may/should be included in the log book, but no loose sheets allowed. Any such sheet must be taped/glued/stapled into the book. A written note of the date, time and circumstances belonging to that particular data set or graph should be there as well.

Perform/record your data evaluation in the log book as well. The graphs that do not make it to the final report should be placed in the logbook.

Data evaluation in your logbook

Consider the following data, taken for some situation where supposedly the current is proportional to the square of the voltage; $I = V^2$.



In a table the data are not particularly instructive. The graph on the top right side shows this data in a graphical format. Is it a quadratic relationship? Hard to say; it may be perhaps cubic. The two lower graphs show $I^{0.5}$ vs. V (left) and I vs. V^2 (right). The lines are guide to the eye, not the results of a fitting procedure. Nevertheless, it is much clearer that the quadratic dependence is at least nearly true. Is the departure from the "pure" quadratic dependence (clearly seen on the left-hand graph) significant? Maybe, maybe not. No error bars are indicated, so we can't tell. The deviation might be due to a systematic error in the measurement - or could it be a true departure from the supposed physical dependence between I and V ? This is where your skill as an experimentalist comes in, *and why it is important to keep a good lab notebook with data plotted as it is taken.*

Writing Experiment Reports

The main goals of your report are to present your results to an educated reader and to convince that reader that those results are correct. Some points to consider in achieving these goals are as follows:

- The report must be logically organized to support your conclusions. Chronological organization is not satisfactory.
- Your report must demonstrate that you have understood the equipment and have made appropriate experimental checks to confirm the validity of your data. Do not just copy descriptions of the apparatus from the write-up or other literature. The equipment never works the way it is supposed to. You must show that you have discovered and understood the various pathologies present.
- It is necessary to include some description of the physics or theory of what you are doing in order to make your results intelligible. This discussion should be well focused and kept to the absolute minim required for a clear discussion of your results. If you must include such things as derivations, use an appendix and do not interrupt the logical flow of your report.
- Error analysis: The uncertainty in your data is as important as the data. You should obtain the theoretical background for error analysis from Bevington and Robinson. You must show that you have understood the various uncertainties in your measurements and apparatus and have done appropriate error analysis to determine the accuracy of your final results. If you use formal error analysis, be sure you have an intuitive understanding of the results.
- You may use the computers in the lab or any other computer to which you have access. You may use any programming language or software package you choose, but you are responsible for knowing what a "canned" data-analysis software package does and demonstrating before you use it that it gives correct results. (See the handout on least-squares fits using the EXCEL spreadsheet, and/or the Turbo Pascal programs in Bevington and Robinson.)
- You should compare your results to similar results in the literature. You should learn how and where to find published data. The first step may be the "CRC handbook" (always available in the lab), but you may want to go well beyond that.
- Don't "fudge" your results. Try to come up with a logical reason or reasons for discrepancies between your values and others. Hopefully you will be able to explain any differences. Random speculation is not useful. You must be able to support your conclusions. Obviously, if you have analyzed your data while you are doing the experiment, you have the best chance of finding out what happened if something went wrong.
- Always give full references to other work which has been used or quoted in your report.

If you are not familiar with scientific word processors, this would be a good time to learn. But remember, while a stylistically clear presentation is very important, it does not compensate for poor data or analysis or an illogical presentation. With this in mind, we

give below some information on common practice for the preparation of papers for publication in physics and astronomy. While LaTeX is predominant, any scientific word processor is acceptable, e.g. Word using the equation editor. Remember, the main goal is clarity. Beauty is secondary. In any case the general structure of your report should follow the APS guidelines, i.e. abstract, introduction, etc.

Reports should be formatted according to the guidelines published by the APS for [Physical Review](#) (physics experiments), or the AAS (astronomy experiments). We recommend writing your report using the **LaTeX** markup language. LaTeX (.tex) files are ASCII files, and can be created using any text editor. The LaTeX software converts the .tex file into a binary .dvi (device-independent) file, which can then be converted to postscript using **dvips**, or to other printable styles (e.g. **pdf**). The LaTeX software is installed on most departmental computers, and can be downloaded freely from the Internet (for example, TeX for Windows is available from the [MiKTeX](#) site). LaTeX is a very versatile language that can be used on almost any computer operating system.

LaTeX uses style (.sty) files to control the design of the output text. Many physics and astronomy journals today require that submitted paper be formatted using LaTeX, and have written style files that format user's text appropriately. Since you will soon be writing real papers in these styles, now is a good time to learn them.

- The American Physical Society uses the [RevTeX](#) style. Reports on physics experiments should be written in the **Physical Review** style using **RevTeX**. The [Physical Review Style and Notation Guide](#) tells you everything you need to know about writing a paper in the correct style for the Physical Review.
- The [American Astronomical Society](#) also publishes [style guidelines](#) for authors. The AAS style is called [AASTeX](#).

You must submit your lab log book along with your report. In principle, the report should be readable without the logbook, but you may reference your log for original tables of data which are presented graphically in your report.

By using the appropriate style files, the format of your report will resemble a journal article (see for example recent copies of Physical Review or Astrophysical Journal in the Library). Some appropriate examples are available in the reference lists for the experiments. The outline of one common format is given below; however variations are possible.

- The cover sheet of the report must contain the name of the experiment, your name, your lab partner's name and the date the report was submitted. If this information is not there the report will be returned without grading.
- The report should have a descriptive title reflecting what you actually did and an abstract of 200 words or less in which you summarize your results, including numerical values with units and errors.
- The main body of the report should contain

1. A clear statement of what your report is about.
 2. An **SHORT** introductory discussion of the physics needed to understand what you are doing. There is no need to copy or paraphrase large portions of physics textbooks (or the Lab Notes) to your report.
 3. A discussion of how you did the measurements: equipment, technique, experimental checks to verify validity of data, etc.
 4. Analysis of your data including error analysis and perhaps presentation of more detailed aspects of theory for comparison.
 5. Representative graphs. There is no need to provide each single graphs you created on your computer during the data analysis, but a few well selected representative graphs are very important, so that the reader can judge the accuracy and reliability of your work.
 6. Discussion of the significance of your results. i.e. what does your data demonstrate about physics. You should compare your results with results from any similar experiments in the literature. Be sure your conclusions are logically defensible.
- The last section of the report contains the list of references.

Tables

- Columns have explanatory headers
- Units are reported in column header
- Range of numbers should be reasonable
- Do not report insignificant digits (Excel users beware!)
- Errors in data should be there, may be in separate column
- *Always* give it a caption.

A poorly formatted table

Table 1: Results of test run 3. **A Bad Table:** This table is needs to have a better

| Distance | Time, sec |
|-------------|------------|
| 0.000020(1) | 12.200001 |
| 0.000041(2) | 20.39999 |
| 0.00080(3) | 35.8010001 |
| 0.000019(2) | 41.300001 |

caption so that the reader doesn't have to dig through your report to figure out what your are showing, and the data is poorly presented. Let's look at the columns separately: In the first column, the data is presented without a unit, and leaves the reader wondering if the distance is presented in nano-meters, or parsecs. The values are also presented with too many leading zeros (which don't

convey much information). In the second column, data is presented with too many significant figures, and the size of the uncertainty is not indicated. Also, the unit should have been presented in SI units (the unit is "s" not "sec").

A well formatted table

This is a better presentation of the same information shown above. Notice that the table caption tells you what has been measured, as well as "when" the data was taken. There is enough information in the caption to uniquely identify when, where and how the data was collected. In addition to the table caption, the columns are properly labeled with SI units which are chosen so that the data magnitude lies between approximately 0.001 and 1000 (it might have been better to choose a standard SI magnitude prefix, but that's a quibble). The values in the table all have experimental uncertainties, and have been truncated to the proper number of significant figures. In addition, the decimal places have been aligned so that it is easy to compare the relative magnitudes.

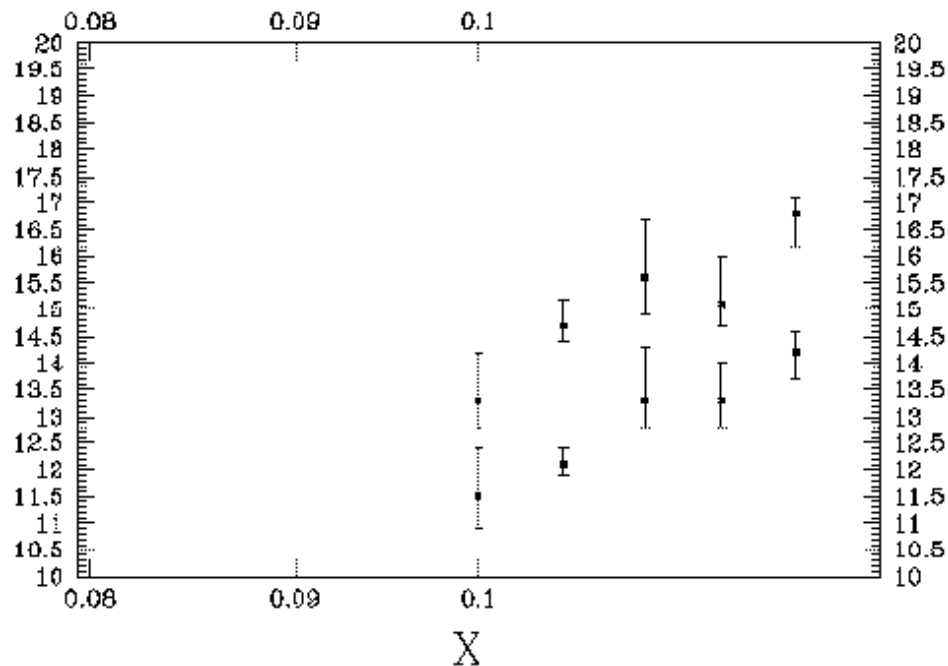
Table 1: Results of test run 3: spring regulator setting versus time of flight.

| Distance | Time |
|-----------------------|----------|
| [$\times 10^{-5}$ m] | [s] |
| 2.0(1) | 12.2(3) |
| 4.1(2) | 20.4(5) |
| 80.(3) | 35.8(16) |
| 1.9(2) | 41.3(2) |

Figures

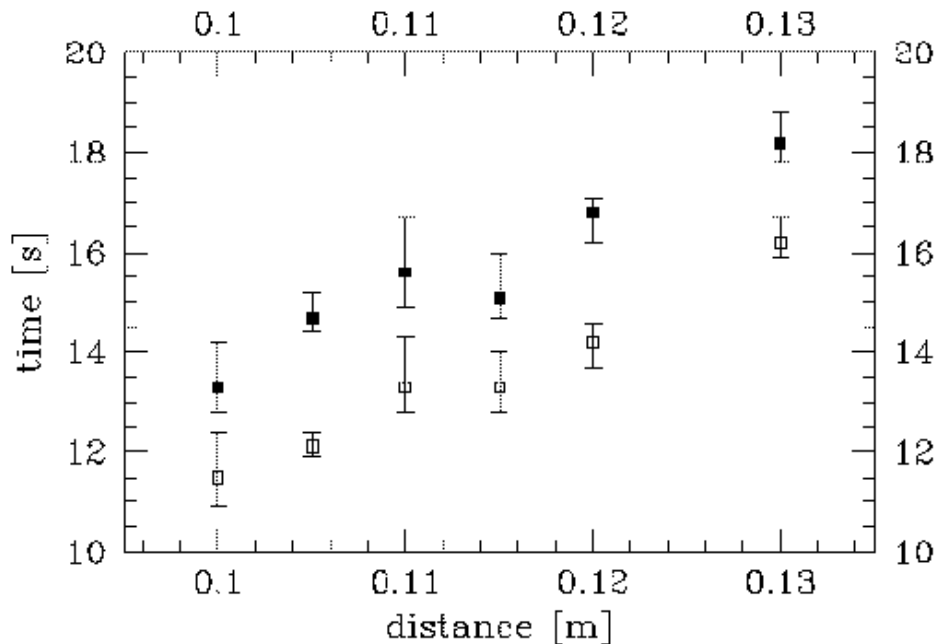
- Proper choice of axes: which variables? sensible limits
- Label axes, with quantity and units
- Large enough symbols/labels/ticks/anything to read well
- Data points:
 - Should be large, and different for different data sets (shape, size, color)
 - Should have error bars
 - Should be explained in caption, or if very many different ones, in legend
- *Always* give it a caption.

A poorly drawn figure:



This figure has several problems. First, the captions on the X and Y axis are missing, or not explanatory. In general, axis captions should contain the units and name of the variable being plotted. The next significant problem is that the number of tick marks are not matched to the data. There are too few marks on the X axis, and far too many on the Y axis. The tick labels are also too small and may be difficult to read if the figure size is reduced. In addition, the range of the X axis not appropriate for the data being presented and as a result, the figure wastes a lot of space. Further, the same mark is used for both sets of data. The mark is also too small so that it is difficult to read and may not be visible if the final paper is printed at low resolution, or if the paper is photo-copied. In addition to all of these problems, the figure is missing a detailed caption explaining the meaning of the two data-sets.

A well drawn figure:



This figure is dramatically better than the figure presented above. Notice that both axes are labeled with the variable name, and unit. Further the axis ranges have been chosen to spread the data out over the entire figure. The symbols for two data sets are clear and different. With the addition of a detailed caption, this figure is ready to be included in a report.

Having drawn a clear figure, it is important to make sure that it is readable in the final report. This means that you need to make sure that the labels are large enough to be read and that the lines are thick enough to be clearly seen. Remember that your report may be printed or photo-copied in black and white so it's a good idea to avoid color in figures (unless it's really required). If you need to use color, try to choose colors that will have different intensities when printed in black and white.

The Presentation

Since PHY445/515 tries to provide a flavor of real experimental physics research, you are required to make a presentation structured after presentations that you may eventually make at conferences. For this reason, PHY445 students will be expected to prepare a 10 minute talk describing one of the experiments performed during the semester. Similarly, PHY515 students will prepare a poster to be presented in a poster session. Remember that the focus of the talk should be to present results of YOUR work.

Preparing an Oral Presentation

For PHY445/6 students an oral presentation of one of the three experiments is required. Here some ground rules and suggestions are given for a good presentation. Consult your professor before giving your talk. The faculty member in charge on the presentations will give you more detailed instruction ahead of time.

Presentation:

- Talk format: American Physical Society format; duration 10 minutes typical, 15 minutes absolute cutoff including time for questions. Count on about 1 minute per slide, so make judicious use of the limited space and time.
- Presentation should be computer based, e.g. using Power Point. We will provide a computer for the presentation. Alternatively it may be on transparencies and shown on the overhead projector; the blackboard can only be used in response to questions.
- Transparencies and pens can be obtained from the Instructional Laboratory.
- Expect to answer a few questions at the end of the presentation.
- Use the feedback from your experiment's instructor, and improve on your written report and analysis!
- Practice your talk some days before the presentation with your partner; allow ample time for feedback and modifications.

Organization of the talk:

1. Title, author, (partner,) institution, and short outline
2. Introduction (15%):
 - Short history
 - The interest and/or practical applications
 - The underlying physics
3. Body of the Talk (50%):
 - Experimental setup and method
 - Data analysis (fits etc.), and theoretical techniques/assumptions
 - Sources and estimation of statistical and systematic uncertainties and errors
4. Results (30%):
 - Result(s) and uncertainties
 - Interpretation of the results in a physical picture; connection of experiment with theory
5. Short conclusion (5%)

Preparing a Poster for the PHY 515 Presentation

PHY 515/516 students present a poster some time during the third lab period. The poster session is held during regular lab time; the date is announced at the beginning of the Semester. The poster you will prepare serves two purposes:

- Allow the audience to get a quick impression of your work
- Provides a basis for verbal discussions.

The posters are approximately 3' x 4' in size. One way of creating a poster is to use a computer and a good quality printer to make individual pages of text/graphics with LARGE characters, and pasting these pages to the poster board. Alternatively you can use the department's new printer for posters. Several samples of "real" posters can be found in the basement of the Grad. Physics building.

The main components:

- The title - should include the name of the experiment, your name, and your partner's name.
- The abstract - contains the main results, similar to the abstract of a report.
- The relevant theory - summarized, including the most important equations you are using.
- The experimental results - in the form of graphs; numerical results with errors and units.
- Tables of important data you may want to discuss.
- Evaluation of data, error estimates.
- Conclusions.

The posters will be graded by the entire staff. You should be prepared to answer questions about the material presented on the poster. Your original lab notes should be available for the discussion.

Laboratory Safety

Using Cryogenic Liquids Safely

The cryogenic liquids (helium and nitrogen) used in the lab are not toxic but can cause serious injury or death if misused. You should not use these liquids until you have been instructed in their safe use by the staff. The main dangers are listed below.

- Frostbite. These liquids are extremely cold and can almost instantly cause serious damage to any part of your body they touch. Perhaps the most likely danger is from a blast of cold gas hitting your hand as the gas rushes from the dewar containing the liquid. This can happen, for instance, when you open the valve on

a pressurized dewar or when you insert a warm object into a dewar and rapidly boil off the liquid. If you grab hold of an object just taken from the liquid your skin could easily freeze to it. **Never allow the cryogenic liquid to reach your eyes, always wear safety glasses.** Remember, eye surgery is sometimes done by using liquid nitrogen.

- Explosion. A cubic foot of liquid will yield about 1000 cubic feet of room temperature gas. If this gas is held in a closed volume pressures can be generated which are sufficient to cause the vessel to explode. For instance, if you leave a helium cryostat completely sealed off, as the liquid boils off something will give. Liquid helium can freeze air into a solid plug blocking the neck of a storage dewar and leading to the danger of an explosion as the pressure builds. Modern dewars are designed to minimize this risk, but you must always be sure not to leave a dewar open to the atmosphere allowing air to get in.

The experimental dewars in the lab are glass vacuum flasks. Under some conditions they may implode sending glass shards flying in all directions (e.g. into your eyes). The dewars are shielded as they are set up. They should not be handled without proper protection and then only by the staff.

- Asphyxiation. In poorly ventilated spaces, large volumes of gas can be generated as liquids boil off. This may displace sufficient oxygen from the air that life cannot be supported. While this should not happen in the Lab, you should be aware of the possible danger under adverse conditions.

Electrical Safety

Physiological effects of electrical shock depend on the current involved, not directly on the voltage. Organs most sensitive to shock are the brain and the heart. In ordinary lab situations most of the resistance is in the contact through the skin, this resistance is greatly decreased if the skin is moist.

At low frequencies (below few kHz) the main effects are shocks.

- sensitivity threshold is around 1 μA
- painful sensation starts at about 5 μA
- at 10-20 μA sustained muscular contraction occurs; can't let go; contraction of chest muscles may stop breathing
- 70-300 μA : current passing through chest may provoke fibrillation in the heart; very often fatal

It is possible to get dangerous shock with voltages as low as 50V.

Radio frequency currents do not induce shocks but may produce burns or dangerous heating (depending on current density).

Precautions:

- All exposed conducting parts of instruments should be properly grounded.
- All wires, contacts having more than 25 V to ground and capable of delivering more than a few μA of current must be protected against the possibility of accidental contact. Please bring to the attention of the staff any dubious case.
- ***Do not work on powered circuits unless you are absolutely sure that no voltages above 25V can be present.***

Laser Safety

The experiment to study the Doppler free spectroscopy uses diode lasers. Here are some safety considerations about lasers that you should follow.

Diode lasers pose no significant electrical hazards because of their low operating voltages. The eye hazards of lasers depend on the wavelength, operating power and focusing optics. The rapid divergence of diode laser beam gives some protection against eye damage by dispersing the power over a large area. However, collimation or focusing of the beam, as required for most applications, removes this safety factor.

Laser powers of a few milliwatts or less are far from deadly and may not even be felt as a warm spot on your skin. The intensity (power per unit area) of a diode laser GaAlAs (for 780nm) is comparable to sunlight (although it is spread over a much smaller area). Because both sunlight and a laser beam are made of parallel rays, the eye can focus both onto very small spots on the retina. If the eye stares at either the sun or a laser beam long enough, the intensity at the retina can be high enough to cause permanent damage. There are no hard-and-fast rules for exactly how much exposure will cause what type of damage, so caution should be the watchword. However, an inadvertent momentary glance into a milliwatt beam is no more likely to cause instantaneous blindness than an accidental glance at the sun.

The wavelength of the diodes used in the laboratory is 780 nm. The eye is insensitive to those wavelengths, although some people can sense 780 nm as red glow, but the response is only about 0.001 times as strong as to the Helium Neon line (633 nm). Do not be fooled into thinking that a weak looking beam must be very low in power. In fact the invisibility of the radiation removes the eye aversion response that protects you in the He-Ne case.

Notes taken from: Jeff Hecht, *The Laser Guidebook, Second edition*, Mc Graw-Hill, New York (1992).

Radiation Safety and Protection

On several experiments in the Advanced Physics Laboratory you will work with radioactive sources. At this time, these are

- Gamma-gamma angular correlation experiment using ^{22}Na and ^{60}Co γ sources;
- Compton scattering using ^{22}Na , ^{137}Cs , ^{57}Co , and ^{133}Ba γ sources.
- The Mossbauer Effect using a ^{57}Co γ and X-ray source.

Care is always required when handling any radioactive source. You are encouraged to monitor your handling of any source with the radiation dose rate meter in the lab (which reads dose rates in mR/hour). The permanent source at the Compton experiment is a strong γ source. This report gives you a brief introduction into the basic aspects and rules of radiation safety. In order to introduce you to this important and generally unfamiliar subject we touch on additional radiation types, such as neutrons, protons and α particles, and their hazards. You will NOT encounter these in this laboratory.

Radiation Activity

Hazardous nuclear radiation originates from number of sources:

1. The nuclear decay of radioactive sources produces γ rays (energetic photons of energies from keV to many MeV) β rays (energetic electrons and positrons), α particles (energetic helium nuclei), and fission fragments (very energetic heavy nuclei like Barium).
2. Nuclear reactions inside nuclear reactors produce neutrons and radioactive nuclei as well as fission fragments.
3. Energetic charged particle beams at accelerators can produce all of the above particles in nuclear reactions, plus energetic protons and charged mesons.
4. These charged-particle beams themselves represent hazardous radiation, as does cosmic ray radiation, such as muons (μ).

The activity of radiation associated with a source is defined as follows: If a radioactive source contains $N(0)$ radioactive nuclei at a time $t = 0$, then after a time t there remain $N(t) =$

$N(0) \exp\{-t/\tau\}$ radioactive nuclei. Here, τ is the mean life time. The activity A of the source at time t is the number of decays per unit time:

$$A(t) = \lambda N(t) = \lambda N(0) \exp\{-\lambda t\},$$

where the $\lambda = 1/\tau$ decay constant is used. Note that the strength of a source decreases with time.

The nominal strength of the source, and the date when this was the actual strength, is written on each source. The present strength can be calculated if the decay rate (or lifetime) is known.

The units of activity are:

1 Becquerel = 1 Bq = 1 disintegration/sec

1 Curie = 1 Ci = 2.22×10^{12} disintegration/min

1 milliCurie = 1 mCi = 10^{-3} Ci

1 microCurie = 1 μ Ci = 10^{-6} Ci

The Ci is the historical unit, the Bq is the SI unit. Note that each disintegration can involve more than one radiation product emitted.

Mostly you will deal with μ Ci strengths. A mCi source is already strong. The ^{137}Cs in the Compton effect is a 300 μ Ci source. Table 1. shows the radioactivity (in Becquerel) of various sources.

| | |
|---|------------------------|
| 1 adult human | 3000 Bq |
| 1 kg of coffee | 1000 Bq |
| 1 kg superphosphate fertiliser | 5000 Bq |
| The air in a 100 square metre home (radon) | 3000 Bq |
| 1 household smoke detector | 30 000 Bq |
| Radioisotope for medical diagnosis | 70 million Bq |
| Radioisotope source for medical therapy | 100 000 000 million Bq |
| 1 kg 50-year old vitrified high-level nuclear waste | 10 000 000 million Bq |
| 1 kg uranium | 10 million Bq |
| 1 kg low level waste | 1 million Bq |
| 1 kg of coal ash | 2000 Bq |
| 1 kg of granite | 1000 Bq |

Table 1. Radioactivity of some natural and other materials

Energy Deposition of Radiation

Nuclear radiation is hazardous to living tissue because it ionizes directly or through secondary processes the atoms, and breaks up molecules, in the cells. This ionization is proportional to the energy deposited in the material. The energy deposited in a unit of

mass is called the Radiation Dose. Its traditional unit is the rad and the SI unit is the Gray (Gy).

$$1 \text{ rad} = 100 \text{ ergs/gr} = 62.4 \times 10^6 \text{ MeV/gr.}$$

$$1 \text{ Gray} = 1 \text{ Gy} = 1 \text{ Joule/kg, so } 1 \text{ rad} \cong 10^{-2} \text{ Gy.}$$

The Roentgen (R) is an older unit for X rays and γ rays expressing the amount of ionization produced in a unit volume of air. $1 \text{ R} = 0.96 \text{ rad}$ in human tissue, for energies between 0.1 and 3 MeV (which covers most radioactive sources and X-ray machines).

Doses in the range of 100 rads lead to clinical symptoms, millirad doses are the level for which rules exist for generally allowed radiation levels and for radiation protection. Note that the rad does not contain the time over which the radiation dose was obtained, i.e. whether it was absorbed in seconds, or in months.

The human body carries an amazing amount of radioactivity within itself, mostly in the form of ^{40}K and ^{14}C . Table 2 contains a breakdown of annual doses (in rad) received by the human body from (internal) natural sources. In addition, we are bombarded by cosmic radiation (muons) at a rate of about $0.01 \text{ particle /cm}^2 \text{ sec}$, and we are exposed to other sources of natural radioactivity.

| Body content in 70 kg man | | | Annual dose |
|---------------------------|-------------|-----------|----------------------|
| Radionuclide | (picocurie) | (dis/min) | (mrad) |
| ^{40}K | 120,000 | 266,000 | 18 (whole body) |
| ^{14}C | 87,000 | 193,000 | 1 (whole body) |
| ^{226}Ra | 40 | 89 | 0.7 (bone lining) |
| ^{210}Po | 500 | 1,110 | .6 (gonads) |
| | | | 3 (bone) |
| ^{90}Sr (1973) | 1,300 | 2,886 | 2.6 (endosteal bone) |
| | | | 1.8 (bone marrow) |

Table 2. Radioactive doses due to various sources in the human body

The biological damage effect by a given dose depends importantly on the density with which the energy was deposited. Different radiations differ in their effectiveness because they lose energy by different rates as they traverse the body material and thus create different ionization densities.

The rate of energy deposition is easily defined for charged particles, which ionize directly and continuously along their path. It is expressed by the **Linear Energy Transfer (LET)**.

The higher the LET, i.e. the shorter the distance over which a given amount of energy is transmitted to the body tissue, the more destructive is the radiation to the tissue. Table 3 gives some LET values for various charged particles. Electrons have a small LET value except at very low energy. α particles from radioactive sources have typically energies around 5 MeV. Their LET is very large. However, they only penetrate 47 μm into the body and thus present a hazard only if they are ingested. An interesting case are protons: At an initial energy of 100 MeV, their LET is small and they do little damage. At the end of their range, when they have only 1 MeV left, their LET is large and they do a lot of damage. Thus accelerated protons are used for cancer therapy with the energy adjusted so that the beam stops in the tumor. 100 MeV protons travel about 7.5 cm into the human body. Beams for cancer therapy have typically energies above 250 MeV.

| | | | Energy | Velocity | LET | Range |
|----------|-------------------|--------|------------------|-----------------------|--------------------|-----------|
| Particle | Mass ^a | Charge | (MeV) | (cm/sec) | (MeV/cm) | (microns) |
| Electron | 1 | -1 | 0.01 | 0.59×10^{10} | 23.2 | 2.5 |
| | | | .1 | 1.64×10^{10} | 4.20 | 140 |
| | | | 1.0 | 2.82×10^{10} | 1.87 | 4,300 |
| | | | 10.0 | 3.00×10^{10} | 2.00 ^b | 48,800 |
| | | | 100 | 3.00×10^{10} | 2.20 ^c | 325,000 |
| Proton | 1835 | +1 | 1.0 | 1.4×10^9 | 268 | 23 |
| | | | 10 | 4.4×10^9 | 47 | 1,180 |
| | | | 100 | 1.3×10^{10} | 7.4 | 75,700 |
| Alpha | 7340 | + 2 | 1.0 | 0.7×10^9 | 1,410 ^d | 7.2 |
| | | | 5.3 ^e | 1.6×10^9 | 474 | 47 |

- a) Mass is taken relative to the electron mass.
- b) An additional 0.20 MeV/cm is lost by emission of photons.
- c) An additional 2.8 MeV/cm is lost by emission of photons.
- d) Includes only energies imparted locally. About 24 percent of the total energy lost by the alpha particle is imparted to electrons in amounts greater than 100 eV per collision. These electrons are considered to lose their energy away from the track, and their energy loss has not been included in the local energy loss of the alpha particle.
- e) Energy of alpha particle from ^{210}Po .

Table 3. Transfer of energy (LET) per cm in water by charged particles.

| Energy | Attenuation, μ (cm ⁻¹) | | | |
|--------|--|-------|-------|----------|
| (Mev) | Water | Iron | Lead | Concrete |
| 0.01 | 4.99 | 1354 | 1453 | 62.3 |
| 0.1 | 0.168 | 2.69 | 59.4 | 0.400 |
| 1 | .071 | 0.469 | 0.776 | .150 |
| 10 | .022 | .235 | .549 | .054 |
| 100 | .017 | .340 | 1.056 | .055 |

Note: The densities of the above materials, in g/cm³, are as follows:

water, 1; iron, 7.87; lead, 11.35; concrete, 2.35.

Table 4. Photon attenuation coefficients.

Being uncharged, γ rays do not ionize directly, but produce energetic electrons in the material through the photo-, Compton-, and pair effects. These electrons then lose their energy with the same LET as primary ones. However, these conversion reactions have small probabilities, given by $P(x) = \mu x$, where $\mu = 0.07 \text{ cm}^{-1}$ is the attenuation coefficient for 1 MeV γ rays in water. A 1.33-MeV γ - photon from a ⁶⁰Co source travels 16.4 cm between interactions in tissue. Table 4 gives various photon attenuation coefficients. Neutrons also do not ionize directly but react with the nuclei in the tissue, most importantly with hydrogen. The secondary recoils then produce ionization. Thus neutrons lose energy much in the same manner as γ rays. Neutrons of less than 100 keV have an attenuation coefficient $\mu = 10 \text{ cm}^{-1}$ in tissue (density = 1 g /cm³).

The **Equivalent Dose** measures the biological effectiveness of a radiation. A "quality" factor (really a dys-quality) QF is defined that converts the radiation energy into an equivalent biological damage. The unit of the equivalent dose are the rem ("radiation equivalent man") and the SI unit Sievert:

$$1 \text{ rem} = 1 \text{ rad} \times \text{QF}$$

$$1 \text{ Sv} = 1 \text{ Gy} \times \text{QF}$$

Table 5 lists quality factors for various radiations in water. For estimates, one often uses QF = 1 for γ rays and electrons, QF = 10 for fast neutrons and protons up to 10 MeV, and QF = 20 for α particles and heavy ions.

With these well defined basic quantities and units, we can take a quick look at the biological effects of the radiation:

10,000 mSv (10 sieverts) in a short-term dose would cause immediate illness and subsequent death within a few weeks.

1,000 mSv (1 sievert) in a short term dose would probably cause (temporary) illness such as nausea, but not death, and would probably cause cancer many years later in 5 of every 100 persons exposed to this dose.

20 mSv per year averaged over 5 years is the limit for nuclear industry employees and uranium or mineral sands miners.

10 mSv/yr is the maximum actual dose received by Australian uranium miners.

2-3 mSv/yr (approx) is the normal background radiation from natural sources, including an average of 0.7 mSv/yr from radon in air. This is close to the minimum dose received by all humans on earth. This dose corresponds to 200-300 mrem.

0.05 mSv, a fraction of natural background radiation, is the design target for maximum annual radiation at the perimeter fence of a nuclear electricity generating station. In practice the actual dose is less.

1. X rays, electrons and positrons of any specific ionization

$$QF = 1$$

2. Heavy ionizing particles

| Average LET in water | |
|----------------------|----------|
| (MeV/cm) | QF |
| 35 or less | 1 |
| 35 to 70 | 1 to 2 |
| 70 to 230 | 2 to 5 |
| 230 to 530 | 5 to 10 |
| 530 to 1750 | 10 to 20 |
| 1750 and above | 20 |

- For practical purposes, a QF of 10 is often used for fast neutrons and protons up to 10 MeV. A QF of 20 is used for alpha particles and other multiply charged particles. The following values for quality factors may be used for neutrons when the neutron energy spectrum is known:

| Neutron Energy (MeV) | QF |
|----------------------|-----|
| Thermal | 2 |
| 0.0001 | 2 |
| 0.01 | 2.5 |
| 0.1 | 7.5 |
| 0.5 | 11 |
| 1.0 | 11 |

Table 5 Quality factors of various radiation types.

Dose Rates and Radiation Shielding

There are four ways in which we can protect ourselves - time, distance, shielding and containment:

Time: For people who are exposed to radiation through their work in addition to natural background radiation, the dose is reduced and the risk of illness made almost nil by limiting exposure time.

Distance: In the same way that heat from a fire is less the further away you are, so the intensity of radiation decreases the further you are from the source of the radiation.

Shielding: Barriers of lead, concrete or water give good protection from penetrating radiation such as gamma rays. Radioactive materials are therefore often stored or handled under water, or by remote control in rooms constructed of thick concrete or lined with lead.

Containment: Radioactive materials are confined in the smallest possible space and kept out of the environment. Radioactive isotopes for medical use, for example, are dispensed in closed handling facilities, while nuclear reactors operate within closed systems with multiple barriers which keep the radioactive materials contained. Rooms have a reduced air pressure so that any

leaks occur into the room and not out from the room.

A ^{22}Na source provides a good example for shielding. To illustrate this we will briefly go through a quantitative exercise for its β and γ rays.

^{22}Na decays to ^{22}Ne by emitting positrons with a peak energy of 0.45 MeV. ^{22}Ne then emits a γ ray with $E_\gamma = 1.27$ MeV. Mostly at the end of its path the positron annihilates with atomic electrons producing two γ rays with $E = 511$ keV each. Thus each disintegration produces 1 e^+ and 3 γ 's.

A ^{22}Na source with a strength of 1 mCi thus produces $A = 2.22 \times 10^9$ β 's /min which radiate into 4π solid angle. If you hold an open source with your fingers they could intercept the total activity over an area of 1 cm^2 . Each β ray has in average about 1/2 the maximal (end point) energy of 0.45 MeV. Fig. 1 gives the range of β rays in Aluminum as a function of their energy. The range is given in units of area density (mg/cm^2) because in these units the curve applies closely to *all* materials. The range for 225 keV positrons in human tissue ($\rho = 1000 \text{ mg}/\text{cm}^3$) is $50 \times 10^{-3} \text{ cm} = 0.5 \text{ mm}$. The dose deposited by the source is then:

$$\text{Dose/min} = \text{Activity} \times \text{energy/event} / (\text{mass affected}) / 62.4 \times 10^6 \text{ MeV./rad}$$

$$= 2.22 \times 10^9 \times 0.225 / (5 \times 10^{-2} \times 62.4 \times 10^6) = 160 \text{ rad/min.}$$

This is a large dose deposited in the skin of your fingers. Thus the source must be shielded. It takes only a very thin shield to stop the α 's. For instance the range of 450 keV β 's in Aluminum is $150 \text{ mg}/\text{cm}^2 / 2.7 \text{ g}/\text{cm}^3 = 0.055 \text{ cm}$, only 1/2 mm. Since we need the source only for its γ 's the radioactivity is already packaged such that the β 's don't emerge from the source (a closed source).

The γ rays are more penetrating. If I_0 γ 's are hitting your body, the number remaining after a distance d is $I(d) = I_0 \exp\{-\mu d\}$, and the number absorbed is then $A(d) = I_0(1 - \exp\{-\mu d\})$. For human tissue (water) $\mu = 0.071 \text{ cm}^{-1}$ (see Table 3). Thus over a body thickness $d = 50 \text{ cm}$ $A = I_0 \times 0.88$, i.e. 88 % of the intensity (and the energy) is absorbed. However, the whole body dose is very small since the volume and thus the mass over which the energy is deposited is small.

Nevertheless, we need to shield the γ source. As Table 4 and Fig. 2 shows the most effective shielding material is lead. The intensity of 1 MeV γ rays remaining after 2 inches of lead (see Table 3) is $I(5\text{cm}) = I_0 \exp\{-776 \times 5\} = 0.02 I_0$. 2 inches of lead leaves 2% of I_0 ; after 4 inches (10 cm) only 0.043% survives. Thus the Compton experiment shields the source with two lead bricks in all directions.

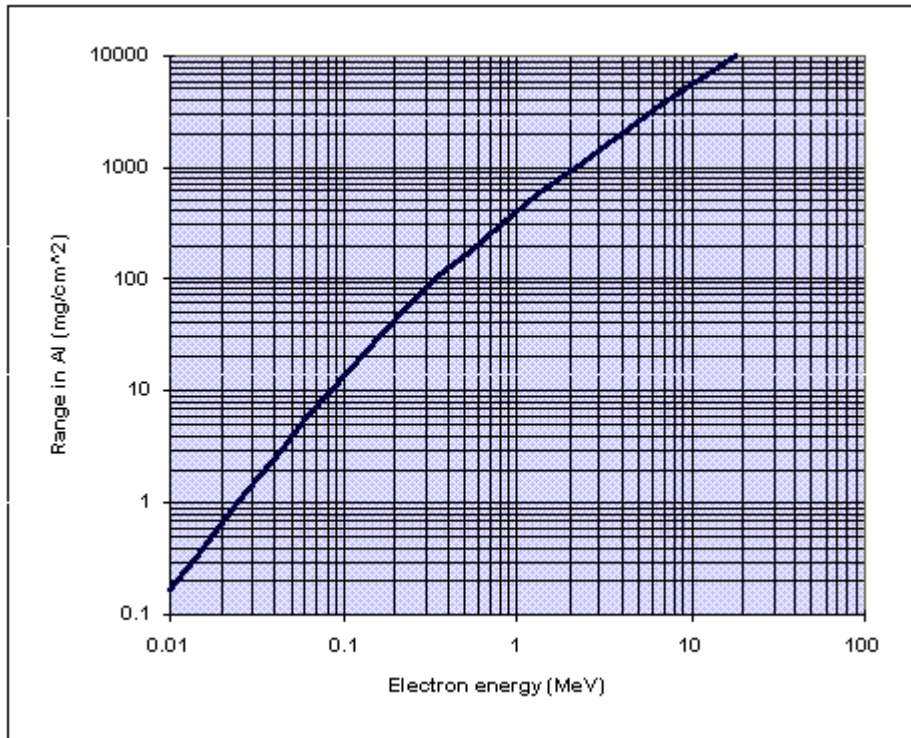


Fig. 1 Range of β rays in Aluminum as a function of energy

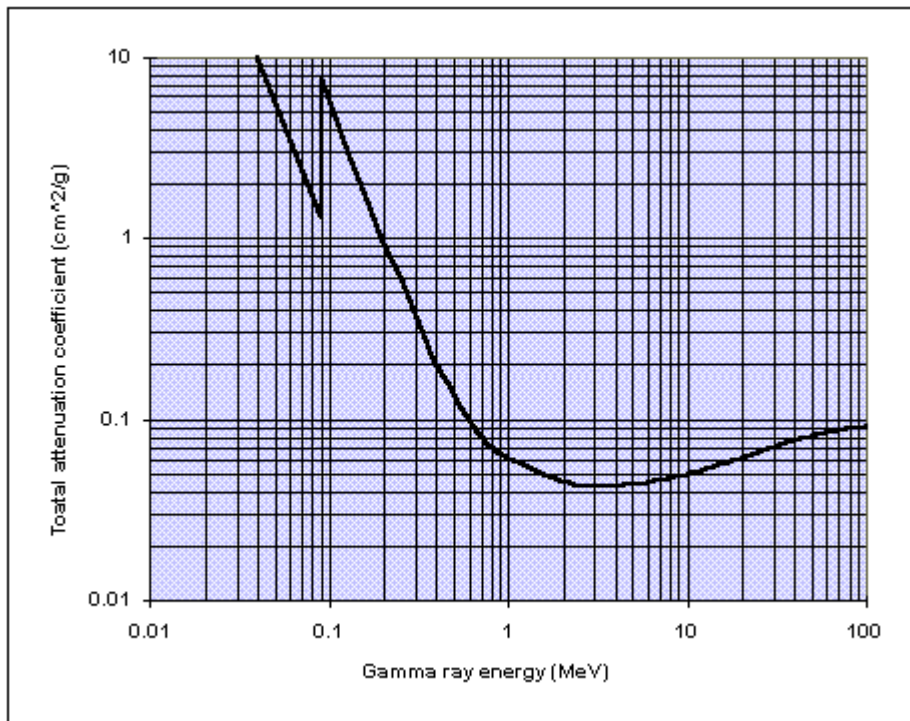


Fig. 2. Attenuation coefficient of lead for γ rays of various energies. Use the density of lead ($\rho = 11.35 \text{ g/cm}^3$) to obtain the attenuation length in cm .

Least Square fits to an arbitrary function using EXCEL

(Hybrid grid-gradient searches of χ^2 surfaces for nonlinear fits)

Introduction

The following should merely be regarded as an addendum to Chapter 8 of Bevington and Robinson's *Data Reduction and Error Analysis*. This is therefore *not* a self-contained manual on "how to do error analysis in the Graduate and Senior Lab and See you later". Referral to Bevington and Robinson for concepts, definitions, theory and the practice of Error-analysis will be necessary. Furthermore what is given here is a mere minimum of how to fit an arbitrary function to a given set data. There are several other methods, which are equally as valid. One can make one's error-analysis really as elaborate as one wants in any way which is scientifically, mathematically and logically sound and accepted. Some of these are also discussed in Bevington and Robinson. Be very careful though of prepackaged error-analysis programs, -routines or magic boxes, if you do not know how they work and what exactly they return as results. It is therefore *not* advisable to use the **Trendline** command in the **Insert** menu of EXCEL. As said, what follows below is a minimum of requirements and just one particular way of doing it. We will proceed by example.

Set-up

Consider for instance the Geiger counter data from an irradiated silver piece used as example in chapter 8 (see Table 8.1). The theoretical shape of the data is given by the function

$$y(t) = a_1 + a_2 \exp(-t/a_4) + a_3 \exp(-t/a_5)$$

For simplicity's sake we will assume the distribution to be Poisson, hence the error in each point is just the square root (Only so when $p \ll 1$; Chapter 2 Bevington and Robinson; be careful when doing real data analysis, whether such assumptions are valid; test!). Also, we will ignore the error in the time, since we will assume it to be far smaller than the error in the counts. If this is not the case, see Chapter 6, page 100 in Bevington and Robinson. This will not however detract from or change the method to fit functions described below.

A first necessity is obviously to enter the data into EXCEL. In most cases you will have to do this manually, though for some experiments it has been automated; in that case the TA will explain it to you. It is useful to leave some rows free at the top; you will see why. HINT: From experience always immediately label your data columns rows appropriately and with the right units; this will make life a lot easier.

You should now have three columns of data: one for the x-coordinate (time), one for the y coordinate (counts) and one for the error in the y coordinate (Δ_{cts}). In the rows left free

at the top just type as text the function you will be fitting, this is convenient as a reminder. Label a set of cells with the appropriate parameter names leaving a set of cells adjacent to the names free. This is where the actual values of the parameters will appear. Next (I usually skip a column to keep clearly separated the fit from the actual data) we create a column for the fitted function as follows. Select the first cell (below the labeling cell) in the column for the fitted function and type there an equal sign followed by the expression of the function, using the proper cell address (A1,B23,AC34, etc.) for value of the function variable and for value of the to be fitted parameters, in which case each element of the cell address should be preceded by a "dollarsign" (\$A\$1, \$B\$23, \$AC\$34, etc). For mathematical expressions such as sine, cosine, exponential etc. use the proper EXCEL command (it can be found under **Function...** in the **Insert** Menu or in the help menu). After entering the expression, pressing return will return the calculated value. If the cell address now is not preceded by a "dollarsign" EXCEL regards the address-referral as *relative* to the original cell (three left, one up), if not as *absolute* (The cell: A1). Thus copying this first cell with the function-expression down will leave the parameter-value unchanged while picking out exactly the proper x-value. This procedure is standard for any EXCEL routine and will be used frequently.

The next column we set up is the column of normalized residuals; this is just the deviation divided by the error for each data point viz. $(y - \text{fit}(y))/\text{error}(y)$. How to set such a column up is explained in the previous paragraph. The definition of χ^2 is the sum of the squares of the normalized residuals, (Bevington and Robinson page 67). To find this value, use the SUMSQ command in EXCEL. Pick an unused cell in the free area left on top and type an equal sign followed by SUMSQ(*argument*) where *argument* is a set of cell addresses. Cell addresses separated by a comma are distinct, while those separated by a colon are continuous viz. A1,A10 are the cells A1 and A10, while A1:A10 are the cells A1, A2, A3 through A10. Do not forget to label your cell. The normalized χ^2 is then the χ^2 divided by the number of degrees of freedom i.e. number of data points minus number of fitting parameters (Bevington and Robinson page 68). The closer the normalized χ^2 will be to 1 the better the fit. Why? See Bevington and Robinson which will also tell you why a normalized χ^2 less than 1 is somewhat of a disaster (amongst others, page 107). We are now completely set up to start performing the fit with EXCEL.

Fitting

To find the best fitting function to the data we want to minimize χ^2 . We do this with the resident **Solver** routine in EXCEL, which can be found in the **Tools** menu. WARNING: OUTSIDE OF THE LAB NOT ALL INSTALLATIONS OF EXCEL HAVE THIS ROUTINE. A **Solver Parameters** submenu will appear asking for the proper parameters. Our Target Cell will be the χ^2 cell, which we want to minimize (min). This we would like to accomplish by changing the values of the parameters a_1, \dots, a_5 hence we enter their respective addresses (in our case \$A\$6:\$E\$6, note the colon and the dollarsigns. the latter are required in the **Solver** submenu). The **Solver Options** are set to perform a hybrid Grid-Gradient search for a minimum in the χ^2 hypersurface in parameter space (page 150ff Bevington and Robinson). There is no need to change the default settings, they are mainly concerned with optimizing the calculation with respect to CPU and memory use.

For those interested look under EXCEL help for the **Solver Options Dialog Box**. It gives a short description of each option.

Before starting the **Solver**, however, read carefully pages 147 and 148 on *Starting values and local minima*. The initial values for the parameters a_1, \dots, a_5 are rather important otherwise the **Solver** search routine could get stuck in a local minimum of the χ^2 surface. We are however looking for the absolute one. Several tries with the **Solver** routine while manually adjusting the parameters if necessary ought to give you the absolute minimum of the χ^2 surface.

Besides using the χ^2 value as a gauge for correctness of the fit it is also very useful to look at the distribution of the normalized residuals. Ideally it should be completely random. If it has any distinguishing patterns, it might indicate that the function you are fitting does not conform to shape of the data. Another kind of function or a combination of two might then be called for as the one to be fitted.

Errors in the parameters

Once we have obtained a best fit to our data we must find some way to extract the errors of the parameters themselves. We do this by performing a χ^2 variation (page 146/7 Bevington and Robinson) for each parameter that we want to know the uncertainty of. Say one wants to know the uncertainty in a_4 . Then one does the following. One performs several **Solver** routines, each time for the values of a_1, a_2, a_3 and a_5 (\$A\$6;\$B\$6;\$C\$6;\$E\$6) while keeping a_4 constant at some manually chosen value, differing for each time one performs the routine. We thus obtain a set of values of χ^2 each corresponding to a value of a_4 . A plot hereof should be a parabola with the minimum at the true χ^2 . The error in a_4 is then given by the difference between the true value of a_4 and that where χ^2 is exactly 1 more than the minimum. The exact value can be found by fitting a parabola to a χ^2 vs. a_4 plot (Figure 8.3 page 146 Bevington and Robinson).

Graphical presentation

Lastly, as data tables are intrinsically rather incomprehensible, we would like to represent our data graphically. This can be done with the **Chart** function in the **Insert** menu or the short-cut **Chartwizard** button. A **Chartwizard** submenu will ask you for the range i.e. the set of cells you want to plot. Easiest is to give one set of x and y values, in this case **Range:** = A11:A69,B11:B59. Note the use of the colons and commas; the equality and dollarsigns are necessary. The rest of the steps of the submenu speak for themselves. Recommended is the X-Y scattering graph, though, it is the most flexible. The graphical tricks that can be performed are innumerable. Clicking on what one wants changed usually gives the submenu to make it possible. Only two useful commands will be mentioned here.$

One is to insert error-bars into the graph. This is done by selecting (clicking on) the data series to which one wants to introduce error-bars. The formula-bar i.e. the bar just above the line of column labels A,B,C,D,...will tell you whether you have done so successfully.

Then **Error-bars** in the **Insert** menu will activate the Error-bar submenu. Naturally we will choose **Custom** Error-bars. The input here is the same format as in Range i.e. an equality sign at the beginning and dollarsigns in front of the cell addresses are necessary. Clicking on a error-bar one can change its shape and format. It is especially advisable to change the **Weight** (thickness) to the minimum, if not the error-bars will be rather fat and clog the picture.

The other useful command is to have the fit and actual data represented in one graph. This is done by the **New Data** command in the **Insert** menu. One is than simply asked for the range (set of cells) which give the y-values for the new data series. The x-values are of course already known. The graph will then show both the actual data as well as the fitted curve. Double clicking on any Data series allows you to change its format (Lines, Dots, sparsing, thickness color, Error-bars(also) etc.).
