X-Ray Physics

MIT Department of Physics

Production and absorption of X-rays; Moseley's law; fine structure of the K lines of the elements. A cooled intrinsic germanium solid-state X-ray detector is used to measure the spectra of X-rays under a variety of circumstances that illustrate several of the important phenomena of X-ray physics. Phenomena observed and measured include the production of X-rays by fluorescent excitation, bremsstrahlung, and electron-positron annihilation and the absorption of X-rays by photoelectric interactions, Compton scattering, and pair production. The energies of the K X-ray lines of numerous elements are measured and compared with the predictions of Moseley's Law. The energy separations and relative intensities of the K_α and K_β lines are measured and compared with the theory of fine structure in the n=2 orbitals.

PREPARATORY QUESTIONS

1. What are the possible ways in which photons with energies in the range from 1 to 2000 keV can interact with matter?

2. How does a germanium solid-state detector work?

3. What atomic transitions give rise to the X-ray lines labeled $K_{\alpha 1}$, $K_{\alpha 2}$, K_β, L, and M

4. According to the CRC Handbook, the total cross section of lead for interaction with 24.94 keV X rays is 48.2 cm^2g^{-1} i.e. the total interaction cross section of all the atoms in 1 gram of lead is 48.2 cm^2). By what factor would the intensity of a pencil beam of such X rays be reduced by passage through 0.01 cm of lead?

5. Plot a curve of the expected energy E of K_α X-rays against the atomic number Z .

INTRODUCTION

In 1895 Röntgen discovered that a high voltage discharge between electrodes in a gas at very low pressure produces a penetrating radiation which causes certain materials to fluoresce visible light. He observed that if the voltage is sufficiently high, the radiation, which he called X rays, can penetrate a hand, casting shadows of the bones on a fluorescent screen. Within a month his discovery created a world-wide sensation. It soon came to be understood that electrons, emitted from the negative electrode (cathode) of the discharge tube, and accelerated by the applied voltage, emit electromagnetic radiation (bremsstrahlung X rays) when they collide with the positive electrode (anode) or the walls of the tube. Röntgen thought, tentatively and incorrectly, that the new rays were longitudinal electromagnetic waves. The high-frequency transverse wave nature of X rays was finally proved sixteen years later by von Laue's discovery of the diffraction of X rays by crystals. The significance of Röntgen's discovery for medical diagnosis was quickly recognized. Kaisers, queens and lesser folk shared the wonder of gazing at the interior structure of living bodies without cutting them open. In the 1930's children could spend hours at the shoe store amusing themselves by wiggling their toes in the X-ray fluoroscope used to judge the fit of new shoes. Millions had their chests regularly examined by high-dose X-ray photography for signs of tuberculosis. Since the 1940's it has been known that irradiation of genetic material in cells by X rays and other ionizing radiations induces changes that can cause cancer. Exposures significantly exceeding that due to natural sources such as cosmic rays and background radioactivity must therefore be avoided. The sources used in the present experiment have been approved by the MIT radiation safety office for educational use. They are not dangerous if handled with appropriate caution. You are urged to determine the exposures you may receive in various manipulations of the laboratory sources by making suitable measurements with the laboratory radiation exposure meter. The consequences of Röntgen's discovery for physics were profound. Six years previously Hertz had discovered electromagnetic radiation (gigahertz radio waves) with wavelengths a million times longer than that of visible light. Röntgen's work showed how to generate electromagnetic radiation with wavelengths ten thousand times shorter. Such wavelengths are comparable to atomic dimensions. As a consequence, X rays proved to be a powerful means for exploring the atomic structure of matter as well as the structure of atoms themselves. Over the next 30 years the discovery and measurement of X-ray phenomena played a central role in the development of the modern quantum theory of matter and radiation. Among the most important landmarks were von Laue's discovery of X-ray diffraction by crystals, Moseley's discovery of the relation between atomic number and the wavelengths of the characteristic X rays emitted by the elements, and Compton's discovery of the quantum character of the scattering of X rays from free electrons. In the present experiment you will use a germanium solid-state X-ray spectrometer to study a variety of phenomena involving the interactions of high-energy photons and matter. The introductory part is a study of X-ray production by irradiation of mat-

ter by electrons and X-rays. It is intended to familiarize you with the equipment and some of the basic physics of X-rays. The rest is a menu of possible studies you can pursue as time permits.

EXPERIMENTAL ARRANGEMENT

The detector is a solid state ionization chamber made of a single crystal of very pure germanium. The crystal is mounted behind a thin beryllium window in a vacuum on a copper "cold finger" which dips into liquid nitrogen contained in a large Dewar. This arrangement conducts heat away from the crystal and keeps the detector at a temperature of 80 K, which assures that the rate at which electrons are thermally excited into the conduction band of the crystal is very low. The crystal is reverse-biased by ≈ -700 volts in order to sweep out any conduction electrons that do appear, either as a result of rare thermal excitations or as a result of excitation by energetic charged particles such as the photoelectrons ejected from the germanium atoms by incident X rays.

CAUTION – The field effect transistor in the preamplifier attached to the Ge detector is easily damaged and costly to replace. Please observe the following precautions:

1. Be sure the preamplifier power is on before turning on the high voltage.
2. Be sure the high voltage is negative.
3. Change the high voltage on the detector slowly ($\sim$ 100 V s^{-1}).
4. Set the bias voltage initially to $\sim$ -700 VDC and do not exceed a bias voltage of $\sim$ -1000 VDC.
5. Ask an instructor to oversee your first use of the system.

An X-ray photon can interact with the germanium crystal by:

1. Photoelectric absorption by an atom, resulting in the disappearance of the photon and the creation of an excited ion through ejection from the atom of an electron with an amount of kinetic energy equal to the original energy of the photon less the energy (binding energy) required to remove the electron from the atom.
2. Compton scattering by a loosely bound electron, resulting in a recoil electron and a scattered photon;
3. Pair creation, if the energy of the incident photon is sufficient ($> 2m_ec^2$). The result is the disappearance of the photon and the materialization of an electron and positron with an amount of energy approximately equal to that of the incident photon less the rest energy of two electrons.
4. Coherent scattering by the bound electrons of an atom, resulting in a scattered photon of slightly reduced energy and changed direction, and negligible excitation of the crystal.

Interaction of an incident photon by process 1,2, or 3 is the start of a complex degradation process that involves multiple Coulomb interactions of the Compton-recoil, photoelectric-ejected, or pair-created electrons with atoms of the crystal, as well as interaction or escape of photons that may emerge from the interactions. The Coulomb interactions excite valence electrons into the conduction band, thereby giving rise to mobile charge that is swept by the bias voltage onto the emitter of the FET in the preamplifier. In the case of a primary photoelectric interaction, the excited ion, missing an inner-shell electron, decays by a cascade of transitions in which electrons from outer shells fall inward, terminating finally with the capture of a stray electron into the valence shell. Each decay transition produces a photon of a certain characteristic energy which may interact in the crystal with the production of more recoil or photoelectrically ejected electrons. In pair production, if the positron comes to rest in the crystal it will combine with an electron and annihilate with the production of two 511 Kev photons traveling in opposite directions. If all the energy of the original photon finally appears as the kinetic energy of secondary electrons in the crystal, then the amplitude of the resulting charge pulse will be accurately proportional to the energy of the incident photon; this is the ideal situation desired in X-ray spectroscopy. On the other hand, if one or more of the secondary photons escapes from the crystal, the resulting charge pulse will be smaller, resulting in a broadened spectral line or, more importantly, in a separate "escape" peak in the spectrum, corresponding to the escape of precisely one energetic photon such as the K X-ray photon emitted by a germanium atom that has photoelectrically absorbed the incident photon. Figure 1 is a block diagram of the electronic equipment . The detector is connected through a preamplifier to an amplifier, and thence to a Perkin-Elmer/Ortec multichannel analyzer (MCA). The preamplifier is permanently mounted on the detector. The amplifier is a spectroscopy grade unit, with coarse gain variable in steps and a continuous fine gain control. The signal pulses from the preamplifier are positive. Positive pulses from the amplifier are fed directly to the ADC input of the MCA which takes 0 -10 volt positive pulses with widths greater than 2 μs. (Use of the bipolar output assures that the baseline is restored after each pulse.) The MCA sorts the pulses according to their amplitudes and records the number of pulses in each of 2048 amplitude intervals. A histogram display of these numbers is generated by the MCA and represents the energy spec-

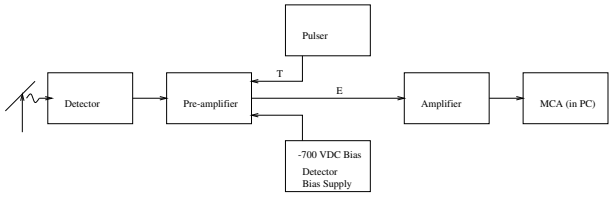

FIG. 1: Schematic diagram of the circuit arrangement for X-ray spectroscopy.

trum of the detected X rays. **A quick-start guide to the Perkin-Elmer Trump-PCI MCA cards can be downloaded from the Junior Lab web server.**

Whenever you start up the system or make a change it is wise to check the proper function of the preamplifier, amplifier, and MCA by examining with an oscilloscope the pulses at the output of amplifier, and to check the overall performance of the system with the aid of the pulser. In particular, you should check that the shape and polarity of the pulses into each unit are correct, and that the amplitudes of the pulses you wish to analyze are in the proper range as they enter the MCA. The output current from the detector is accumulated on a small capacitor connected to the emitter of the input FET in the preamplifier. The capacitor is discharged automatically by an auxiliary circuit whenever the accumulated charge exceeds a certain limit. Each discharge produces a pulse of fixed height that appears in one or two channels of the MCA at the high energy end of the spectrum. The rate of these discharges varies according to the intensity of the radiation being measured. Care must be taken not to mistake the resulting spectrum feature for a line in the X-ray spectrum being recorded.

STARTING UP

Turn on the NIM-bin power supply, the PC, and the oscilloscope. Run the MCA control software called Maestro-32 from the Windows desktop. Connect the amplifier output to the MCA and the oscilloscope. Turn on the high voltage supply and gradually apply the bias voltage of ≈ -1000 volts.

Be sure you apply a negative bias voltage; a positive high voltage bias may damage the detector.

Place the ^{55}Fe source a few inches in front of the Ge detector window. (The window is made of beryllium $\frac{1}{1000}$ inch thick!. A guard has been placed over it to prevent accidental touching and breaking of the fragile foil, which must be as thin as possible to allow low energy X rays to be detected and yet strong enough to hold the vacuum.) Adjust the gain of the amplifier so that at its output the prominent 5.89 keV K_α line of ^{55}Mn appears on the oscilloscope as a concentration of pulses with amplitudes near 1 volt . The amplifier should work with a coarse gain of about 300. Vary the distance between source and detector and note if the amplitude of the line begins to sag due to too high a counting rate. Back off sufficiently to insure a stable response. Accumulate a spectrum with the MCA, and adjust the gains so that the Mn K_α line is centered on the left side of the display, say near channel 70.

OBSERVATIONS

QUANTITIES YOU CAN MEASURE

1. The E versus Z relations (Moseley's law) for the various series of characteristic K and L X rays.
2. The fine structure splittings of the K and L shell energy levels.
3. Ratios of the maximum electron recoil energy to the incident photon energy for Compton scattering of photons.
4. Attenuation cross sections of carbon, aluminum and lead for X rays of several different energies.
5. The jump in absorption cross section at a K edge.

Keep notes of the settings used in all your measurements so you can return to them quickly if desired.

Analyze the spectra as you take them by using the cursor to determine peak position and the full width at half maximum (FWHM), and the region of interest (ROI) feature to determine total counts and area under the peaks. *Do not leave simple analysis of data for later.* In particular, where graphical display of the data is appropriate, have graph paper at hand and make a plot as you go along so that you can see what is happening. **Save the data as a file in the shared-users folder residing on the Junior Lab Server PC (available from the local PC's desktop)** and perhaps also on a floppy disk. Record all pertinent information about each file in your notebook..

PRODUCTION OF ENERGETIC PHOTONS

The purpose of the following experiments is to familiarize you with the various processes in which energetic photons in the energy range above several keV can be produced. The name "X ray" is generally given to such a photon if it is emitted by a free or bound electron and has an energy in the range from 0.1 to 100 keV. Below 0.1 keV lies the "extreme ultraviolet"; above is the region of "gamma rays". Photons emitted directly by nuclei are generally called gamma rays even if their energy is in the conventional X-ray range. The high-energy photon production processes you will explore are:

1. **Bremsstrahlung** ("Braking radiation"): An energetic electron which undergoes a sudden acceleration caused by interaction with a high-Z nucleus has a high probability of emitting a "bremsstrahlung" photon with an energy in the range from 0 to the full kinetic energy of the electron. This is the process that occurred in Röntgen's discovery experiment when electrons accelerated in the discharge struck the glass wall of the tube.

2. **X-ray fluorescence induced by energetic charged particles:** When an energetic electron or other charged particle (e.g.an alpha particle) interacts with an atom it may eject an electron from one of the inner shells. The resulting ion relaxes from its excited state by a cascade of transitions in which electrons from outer shells fall inward until no vacancy remains. Each transition gives rise to a photon with a characteristic energy. A photon produced when an outer electron falls into a hole in the n=1,2, and 3 shells are called K, L, and M X rays, respectively.

3. **X-ray fluorescence induced by X rays:** A photon with sufficient energy may interact with an atom to eject an electron from an inner shell in what is called a "photoelectric" absorption process. The subsequent relaxation of the excited ion produces the same characteristic X rays as in electron bombardment.

4. **Emission of photons by the decay of excited nuclei:** One example of this process is the decay of the excited nucleus of ^{57}Fe created by the beta decay (K electron capture) of ^{57}Co as described in Melissinos on p. 272. Under certain circumstances this decay yields photons with energies in an extremely narrow range near 14.4 keV which can be exploited in "Mössbauer" spectroscopy. In addition, decay of the excited ^{57}Fe electronic structure which results from the capture of the K electron gives rise to the characteristic X-ray photons of iron.

5. **Annihilation of electron-positron pairs:** Some unstable nuclei (e.g. ^{22}Na) undergo a beta-decay process in which a proton in the nucleus is transformed into a neutron with the emission of a positron (anti-electron) and an electron neutrino according to the scheme

$$p \Rightarrow n + e^{+} + \nu_e \tag{1}$$

The ejected positron eventually interacts with an electron in the surrounding material and annihilates with the production of photons. Such annihilations usually yield two photons which, in the center of mass, travel in exactly opposite directions and each with an energy of precisely $m_e c^2$ in accordance with the conservation of momentum and energy.

EXPERIMENTAL PROCEDURE

Production of bremsstrahlung and characteristic line radiation by high-energy electron bombardment of lead.

The classic way to generate X rays is to bombard a metal target with a beam of energetic electrons. A typical commercial X-ray generator, such as one used by a dentist or in an airport baggage inspection system, employs a vacuum tube in which electrons, emitted from a filament-heated cathode, are accelerated by field supported by a high-voltage (50 keV) power supply, and strike a metal anode target. The spectrum of the X rays radiated from the target consists of a bremsstrahlung continuum with an energy cutoff at $\frac{hc}{\lambda} = Ve$ (V is the voltage of the power supply), and narrow lines with wavelengths characteristic of the target material. In this experiment the source of energetic electrons is several millicuries of ^{90}Sr which decays according to the scheme

$$^{90}Sr_{38} \Rightarrow^{90} Y_{39} + e^{-} + -\nu_e$$
$$^{90}Y_{39} \Rightarrow^{90} Zr_{40} + e^{-} + -\nu_e$$

The source is contained in an aluminum and lead-lined container (see Figure 2) which can be placed on the small wooden stand next to the detector so that the hole behind the lead shutter is aligned with the entrance window of the detector. **CAUTION: Avoid exposing your hands to the radiation emerging from the hole in the lead lined box. The ^{90}Sr source is quite strong (several millicuries) and the electrons which it emits readily bounce off lead nuclei in all directions, including out through the hole.**

Observe the spectrum of pulses with nothing in the 45° slot. Then put a thin (1/4" thick) slab of lead in the 45° slot so that the beta particles (energetic electrons) emitted by the source strike the slab. Observe the spectrum of the pulses produced by the bremsstrahlung radiation from the lead target, and identify the characteristic X rays of lead. Using the K_α lines of lead and the 511 keV line from the ^{22}Na calibration gamma-ray source as calibrators, determine the high-energy cutoff of the bremsstrahlung spectrum. How does it compare with the end point of the energy spectrum of the beta rays from ^{90}Sr and ^{90}Y (consult the CRC tables)? Replace the lead slab with other materials and observe their characteristic X rays. The ^{90}Sr source is shielded in the lead container so as to confine the directions of its emissions

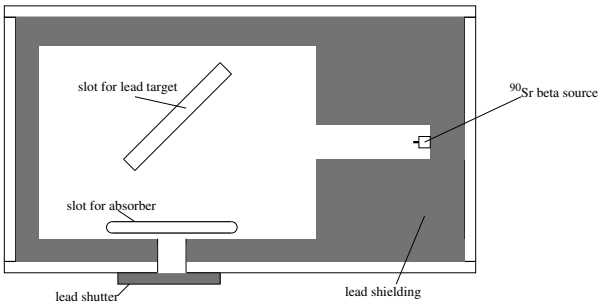

FIG. 2: Arrangement for producing bremsstrahlung X rays by high energy electrons emitted in beta decay of ^{90}Sr and ^{90}Y, and studying the absorption of the X rays by various materials.

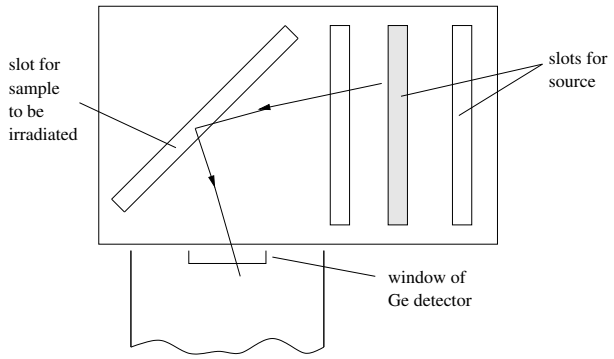

FIG. 3: Arrangement for irradiating samples to produce fluorescent X rays.

to the target area. However, some scattered electrons emerge from the target along with the bremsstrahlung. You can estimate the electron contamination in the exit beam by measuring the change in the counting rate when thin (1 mm) layers of plastic are inserted between the window and the detector, or by deflecting the electrons with a strong permanent magnet.

X-RAY INDUCED FLUORESCENCE

Measure the fluorescent radiation emitted by various target materials when they are irradiated by X rays from the ^{55}Fe source. Arrange the geometry (see Figure 3) so that the target is as close as possible to the detector, but the X rays from the source can not enter the detector directly. Identify the features you see. (Note that ^{55}Fe decays by K-electron capture, leaving an excited ^{55}Mn atom which decays by K X-ray emission.) What is the lowest energy K line you are able to detect? The highest? What are the limiting factors? Put the X-ray "howitzer" in front of the detector and dial an X ray. Inside the howitzer is a strong source of gamma rays (^{241}Am) and targets of various elements which can be placed in the flux of gamma rays by a turn of the knurled wheel. Record, measure and explain the resulting spectra, i.e. try to identify each line in each spectrum and explain its nature and origin.

Emission of nuclear gamma rays and characteristic X rays by radioactive atoms

Place the ^{133}Ba gamma-ray calibration source in front of the detector window. Adjust the gain so that the energy spectrum utilizes the full dynamic range of the MCA (2048 channels). Measure the spectrum and with the aid of the CRC tables identify as many of its features as you can.

ELECTRON-POSITRON ANNIHILATION RADIATION

Place the ^{22}Na (yellow tip) gamma-ray calibration source near the Ge detector, turn the gain down by steps until the spectrum of pulses produced by photons with energies in the energy range from 0 to 1.5 MeV can be seen. Accumulate the spectrum until the statistical fluctuations are well smoothed out. Identify the lines and explain their origins. Identify the continua of pulses produced by Compton scattering of the monoenergetic gamma rays in the Ge crystal; measure the energies of the Compton edges. Explain the relation between the energies of the photopeaks and the Compton edges in terms of the theory of Compton scattering.

Do the same with the ^{60}Co source (blue tip). With sufficient statistics you may see a tiny blip in the spectrum near 0.511 MeV. How do you account for that?

OTHER EXPERIMENTS THE PROPERTIES OF K AND L X RAYS: MOSELEY'S LAW

The purpose of the following observations is to measure with precision the properties of the characteristic X rays emitted by various elements, and to understand in terms of the theory of atomic structure how the properties vary with Z. In particular, you will measure the relative energies and relative intensities of the K and L X-rays as functions of atomic number. The analysis of the energies will provide a check of Moseley's law. The relative intensities and separations of the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines can be compared to the values expected from theoretical considerations of the effect on energy levels of the spin-orbit interactions of the L-shell electrons. Adjust the gain so that the K lines of lead are at the far right end of the MCA histogram. Record their channel numbers. Place the variable energy X-ray source (see the specification sheet taped to the wall next to the radioactive source storage cabinet) in front of the detector and record the

channel numbers of the K lines of terbium (Tb), barium (Ba), silver (Ag), molybdenum (Mo), rubidium (Rb), and Copper (Cu). In each case, obtain about 10,000 counts in the major peak and measure as precisely as you can the peak position, the FWHM and the total count under every significant peak observed. You may see peaks from the americium gamma rays, neptunium X-rays, escape peaks, etc. Search for L lines at low energies for the higher-Z elements. In each case, print the MCA display, documenting the run in your notebook. To simplify the analysis try to cover the total energy range of the various spectra with one setting of the gain. It is wise to run through the series quickly several times until you get the settings just right, and then take your final data. For the terbium spectrum, record the counts per channel over the K_α and K_β peak regions, including the wings of the peaks, so that you will be able to make a detailed analysis of the structures of the lines. To get data on lead and other high-Z elements you can use the ^{90}Sr bremsstrahlung generator with various materials placed in the bremsstrahlung beam. You can also excite fluorescent X-ray emission from high-Z elements with the gamma rays from the calibration sources. To study fluorescent emission in low-Z elements, increase the gain to place the copper K lines at the right hand end of the display. Measure the spectrum of the ^{55}Fe source and the spectra of various low-Z elements fluoresced by the ^{55}Fe radiation. (See how low in Z you can go.)

ANALYSIS

Try to identify all the lines that you can see in the various spectra. The most prominent are probably the K lines. Others may be "escape peaks" (see above), L lines, or background radiation from radioactivity in the room. Moseley discovered that the wave numbers, $\nu = \frac{1}{\lambda}$, of characteristic X-ray lines emitted by the elements under electron bombardment are related to the atomic number, Z, by equations of the form

$$\sqrt{\nu} = C(Z - \sigma) \tag{2}$$

He measured the wave numbers directly by Bragg reflection spectrometry, using crystals with known lattice spacings. The energies are related to wave numbers by the Planck formula

$$E = \frac{hc}{2\pi k} \tag{3}$$

where h is Planck's constant, c is the speed of light, and k is measured in wavenumbers (cm^{-1}). In terms of X-ray energies the Moseley relation is

$$\sqrt{E} = C'(Z - \sigma) \tag{4}$$

Your data provide relative measures of the X-ray photon energies in terms of channel numbers n of the peak positions which are approximately proportional to energy.

$$\sqrt{E} \propto \sqrt{n} \tag{5}$$

The essential features of the Moseley law can therefore be revealed by a plot of the square root of the measured channel numbers against the atomic numbers of the emitting elements. Make such plots for the each distinct set of lines ($K_{\alpha 1}, K_{\beta 2}, L_\alpha$, etc.), and determine the values of $C_n\sigma$ in each case. Try to describe a complete and practical set of experiments that would achieve a fundamental calibration of the germanium spectrometer in terms of energy versus channel number. In the present situation, assume that E(^{22}Na) = 511 keV, E(^{55}Fe) = 5.8 keV and that the multi-channel analyzer has a very linear response in between these values. lacking the necessary equipment and time, you will have to "peek" at an established result in order to tie your measurements down to actual energies.

1. Convert all your peak positions and FWHM measurements to energies in keV with estimated errors. Do this with the highest precision that your data justify, and compare your results with the values tabulated in the CRC handbook. Determine the energies of the Ge K lines from data on the identified escape peaks.

2. Determine the ratios of the intensities of the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines and compare with the theoretical expectations based on consideration of the statistical weights of the parent L_{III} and L_{II} states (see Compton and Allison, p. 648).

3. According to an approximate treatment of the spin-orbit interaction (see Compton and Allison, p. 606), the doublet separation in energy should vary with Z as $(Z - \sigma)^4$. Compare this prediction with your data.

4. (for theoretical hot shots) For the case of Tb, verify that the magnitude of the spin-orbit splitting is that given by perturbation theory.

   A term diagram for the X-ray levels of a heavy element, showing the transitions giving rise to the K, L, and M lines can be found in Compton and Allison (1935), p. 630 on the Junior Lab Library shelf.

   What quantum rule forbids the transition from L_1 to K. Given this fact, how could you determine experimentally the value of the energy L_1 level of Tb?

ABSORPTION OF X RAYS

Measure the absorption coefficient of X rays of several widely different energies in several metals of widely different atomic number Z by inserting thin sheets of the metal between various sources of monoenergetic X rays and the detector. (The X-ray howitzer is a convenient source of monochromatic X rays with energies in the range from 6 to about 60 keV. The gamma ray calibration sources provide monochromatic photons up to 1.3 MeV). A typical measurement might be carried out as follows: Place the howitzer about 10 cm from the detector with the dial turned to Ag. Measure the rate of pulses in the Ag K_α and K_β lines using the facilities of the MCA. Place a copper (lead) foil of measured thickness between the source and the detector and as close to the source as possible. Measure the reduced rate. (A good choice of thickness is one that reduces the rate by a factor of about 2). Repeat the measurement with a second and third foil. Plot the natural log of the rate against the thickness measured in g cm^{-2}. Check whether the data conform to the formula for exponential attenuation, namely

$$I(x) = I_0 e^{-\mu x} \tag{6}$$

or

$$ln\left[\frac{I(x)}{I_0}\right] = -\mu x \tag{7}$$

where x is the thickness and μ is a constant called the mass attenuation coefficient. The thickness is related to the linear thickness t and the density ρ by

$$x = \rho t \tag{8}$$

Fit a straight line to the log plot and from the slope determine the mass attenuation coefficient and the attenuation cross section. Repeat for each energy and each element, and summarize your results in tabular and graphical form. What regularities do you perceive? (You may find log-log plots of cross section versus energy or Z useful). Using the Ag source in the howitzer, compare the absorption cross sections of cadmium and palladium for the K_α and K_β lines of silver. Can you explain the difference in light of the fact that cadmium and palladium do not differ much in atomic number? You can observe a similar difference between the absorption cross sections of various metals with Z near 25 for X rays from the ^{55}Fe source.

RELATION OF K-EDGE ABSORPTION TO K-LINE EMISSION

Place a lead sheet in the beam of electrons emitted by ^{90}Sr in the plastic box to produce a continuum spectrum of bremsstrahlung radiation. Insert a foil of molybdenum in the slot between the lead target and the detector. Observe what goes on in the spectrum recorded by the detector in the range of energies around the K_α line of molybdenum. Observe the K_α absorption line, and explain how its place in the spectrum is related to the K_α line.

CHALLENGE

1. Place a ^{133}Cs calibration source (green) close to the detector window, reduce the amplifier gain so as to place the needle-sharp 661.63 gamma-ray line near the right-hand side of the MCA display (use full 2048 channel display). Don't be confused by the higher level reset pulse from the detector preamp. Accumulate the spectrum for about one hour. Measure channel positions of all the features you can discern. Download the spectrum for later detailed analysis. Try to provide a physics explanation for each of the features, making good use of the data on gamma-ray and X-ray energies in the CRC Handbook.

2. Do the same with the ^{133}Ba calibration source (black).

3. Determine the composition of the United States quarter. With the system calibrated by X-rays of known energy, try to determine the elemental composition of the United States quarter coin by measuring the spectrum of its fluorescent X-rays

1. Atomic structure and the explanation of the Moseley relation between K-line energies and Z.

2. Compton scattering.

3. The classical theory of Thomson scattering and the Thomson cross section of the electron.

4. The bremsstrahlung spectrum (see "High Energy Particles", B. Rossi, Prentice hall,1952).

5. Attenuation of an X-ray beam in matter - (see "The Atomic Nucleus", R. Evans, McGraw Hill).

6. The theory of the lithium-drifted germanium (GeLi) detector.

[1] Moseley, H.G.B., The High-Frequency Spectra of the Elements , Phil. Mag. 6, 26, 1024 (1913), Part I; 6, 27, 703 (1914), Part II, QC.P568 Science Library Journal Collection

[2] A. H. Compton and S. K. Allison, X-Rays in Theory and Experiment (D.Van Nostrand, NY, 1935), QC481.C738 Physics Department Reading Room
[3] Knoll, G.F. Radiation Detection and Measurement,(Wiley & Sons NY 1979), pp. 492-502, QC787.C6.K56 Physics Department Reading Room
[4] CRC Handbook of Physics and Chemistry
[5] Compton, A.H., "The Spectrum of Scattered X-Rays", The Physical Review, Second Series, Vol. 22, No.5, November [1923]
[6] Way, K., "Atomic Data Related to X and XUV Radiation" from Atomic Data and Nuclear Data Tables Vol. 22, pp.125-130 [1978]
[7] Montenegro, E.C., Baptista, G.B., and Duarte, P. "K and L X-ray Mass Attenuation Coefficients For Low Z Materials", Atomic Data and Nuclear Tables, Vol 22, 1978 p.131-177
[8] Arthur Holly Compton's Nobel Lecture (1927)
[9] Wilhelm Conrad Rontgen's Nobel Lecture (1901)
[10] Karl Manne Georg Siegbahn's Nobel Lecture (1924)

X-RAY PHYSICS EQUIPMENT LIST

Model	Description	Contact
Canberra 71255E	Ge(Li) X-Ray Detector	www.canberra.com
Canberra 7600	Cryostat	www.canberra.com
Canberra 1708P	Pre-Amplifier	www.canberra.com
HP 54601A	Oscilloscope	www.agilent.com
Ortec 428	HV Power Supply	ortec-online.com
Ortec 472	Spectroscopy Amp.	ortec-online.com
Ortec 4006	Minibin and Power Supply	ortec-online.com
MIT	Samples/Sources	