X-Ray Physics

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This experiment investigates the production and absorption of x rays. A high-precision 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 bremsstrahlung emission; fluorescent excitation of x rays, which allows spectroscopic identification of unknown elements in a sample; electron-positron annihilation; and the absorption and attenuation of x-ray beams 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 Kα and Kβ lines are measured and compared with the theory of fine structure in the $n = 2$ orbitals.

PREPARATORY QUESTIONS

Please visit the X-ray Physics chapter on the course website to review the background material for this experiment. Answer all questions found in the chapter. Work out the solutions in your laboratory notebook; submit your answers on the course website. [**Note:** Not available to OCW users]

SAFETY

Personal Health and Safety

The carcinogenic properties of x rays and other ionizing radiations have been known since the 1940s. 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 Program for educational use. They are not dangerous if handled with appropriate caution. You are urged to determine the exposures you may receive in var-ious manipulations of the laboratory sources by making suitable measurements with the laboratory radiation survey meters.

The two primary sources of radiation in this experiment, ^{241}Am (an alpha emitter) and ^{90}Sr (a high-energy beta emitter), should be transported from their storage locker to the experiment quickly. For the safety of others in the laboratory, they may never be left out unattended. In particular, the ^{90}Sr source must be positioned during the experiment such that its beam is well contained around the apparatus. Use lead shielding as necessary to minimize radiation in an undesirable direction.

The ^{90}Sr source is contained in an aluminum and lead-lined container (see Figure 3) 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 expos-ing 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 elec-trons which it emits readily bounce off lead nuclei in all directions, including out through the hole.**

Equipment Safety

The detector used in this experiment has a few important operating requirements to keep in mind in order to avoid damaging its delicate and expensive components. Please observe the following precautions:

1. **Never touch the carbon fiber window.** Leave the polyethylene cover on. It only attenuates x rays below 10 keV.

2. **The field effect transistor in the preamplifier attached to the detector is easily damaged and costly to replace.** Be sure the preamplifier is powered (from the back of the NIM bin) *before* turning on the high voltage bias.

3. *Slowly* raise the bias voltage to about +3000 VDC. (Be sure of the polarity!) Be careful when you apply this and take standard electrical safety precautions.

4. Ask an instructor to oversee your first use of the system and ensure there is enough liquid nitrogen in the cryostat.

I. INTRODUCTION

In 1895, Wilhelm Conrad Röntgen (or "Roentgen" in anglicized typography) 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 [6]. He observed that if the voltage exceeds about 30 kV, then the radiation — which he called x rays — can penetrate a hand, casting shadows of the bones on a fluorescent screen. 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.

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. Röntgen was awarded the first Nobel Prize in Physics in 1901 [6].

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 matter 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.

II.   THEORY

The sub-discipline of x-ray physics involves a certain amount of nomenclature and notation that you will need to become familiar with before performing this lab. Much of the older literature in the field uses the so-called "Siegbahn notation" to describe x rays emitted during transitions between atomic electron configurations. A terminology diagram showing the transitions giving rise to the K, L, and M lines appears in Reference [7, p. 630] and is reproduced in Figure 1. Table I further explains the correspondence of the level naming scheme to electronic configurations. In more recent times, a more intuitive "IUPAC notation" has become dominant (see Reference [3]). In this system, transitions between x-ray levels are denoted by the level symbols for the initial and final states separated by a minus sign. The initial state is placed first, irrespective of the energetic ordering. You should become familiar with converting between both notations. Table II shows the correspondence between the two notations. As an example: $K-L_3$ in IUPAC notation is $K\alpha_1$ in the Siegbahn notation. Either way, it denotes the filling of a 1s hole by a $2p_{3/2}$ electron.

II.1.   Production of Energetic Photons

The name "x ray" is generally given to a photon if it is emitted by a free or bound electron and has an energy in the range from about 0.1 keV to about 100 keV. Photons emitted directly by nuclei are generally called gamma rays even if their energy is in the conventional

TABLE I. Correspondence between x ray diagram levels and electron configurations. The "−1" superscript in the electron configuration indicates a single electron vacancy in a many-electron system. This table follows that found in [3].

Level	Electron config.	Level	Electron config.	Level	Electron config.
K	$1s^{-1}$	N_1	$4s^{-1}$	O_1	$5s^{-1}$
L_1	$2s^{-1}$	N_2	$4p^{-1}$	O_2	$5p^{-1}$
L_2	$2p^{-1}$	N_3	$4p_{3/2}^{-1}$	O_3	$5p_{3/2}^{-1}$
L_3	$2p_{3/2}^{-1}$	N_4	$4d_{3/2}^{-1}$	O_4	$5d_{3/2}^{-1}$
M_1	$3s^{-1}$	N_5	$4d_{5/2}^{-1}$	O_5	$5d_{5/2}^{-1}$
M_2	$3p^{-1}$	N_6	$4f_{5/2}^{-1}$	O_6	$5f_{5/2}^{-1}$
M_3	$3p_{3/2}^{-1}$	N_7	$4f_{7/2}^{-1}$	O_7	$5f_{7/2}^{-1}$
M_4	$3d_{3/2}^{-1}$				
M_5	$3d_{5/2}^{-1}$				

TABLE II. Correspondence between the Siegbahn (older) and IUPAC (newer) notations. A more complete table can be found in [3].

Siegbahn	IUPAC	Siegbahn	IUPAC
$K\alpha_1$	$K-L_3$	$L\alpha_1$	L_3-M_5
$K\alpha_2$	$K-L_2$	$L\alpha_2$	L_3-M_4
$K\beta_1$	$K-M_3$	$L\beta_1$	L_2-M_4
$K\beta_2^I$	$K-N_3$	$L\beta_2$	L_3-N_5

x ray range. The high-energy photon production processes you will explore are:

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 ranging from zero to the full kinetic energy of the electron. The spectrum of the x rays radiated from the target of an electron beam consists of a bremsstrahlung continuum with a maximum energy cutoff equal to the kinetic energy of the electrons in the beam. For example, for electrons of charge e accelerated by an applied voltage V, the maximum energy in the bremsstrahlung spectrum would be Ve. In this experiment, the source of energetic electrons is a millicurie-level sample of ^{90}Sr, which beta-decays with a 29-year half life and maximum electron energy of 0.5 MeV to ^{90}Y which in turn beta decays with a 64-hour half life and maximum electron energy of 2.3 MeV to ^{90}Zr.

X-ray fluorescence *via* 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
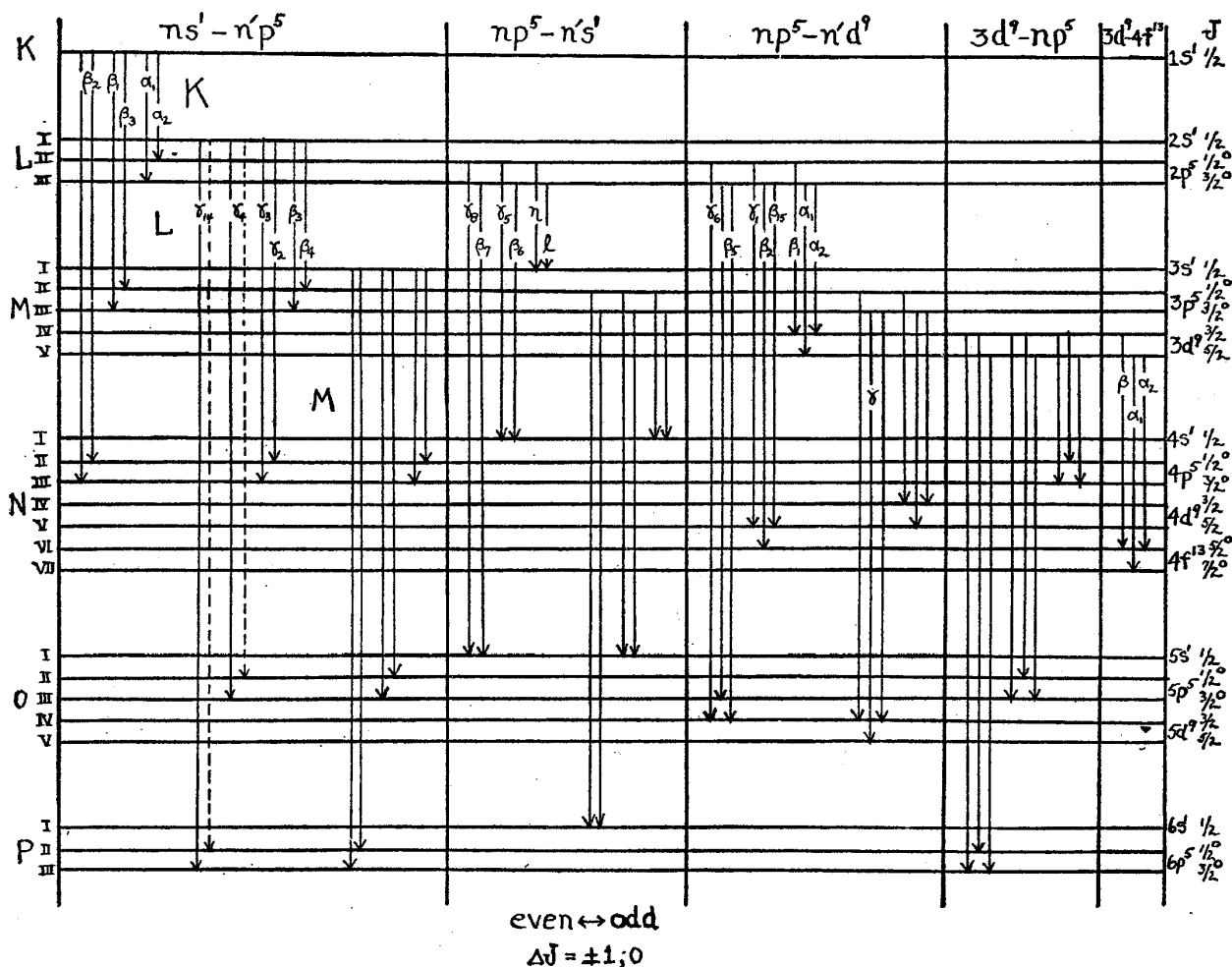
FIG. VIII-17. Qualitative term diagram for x-ray levels, showing lines in the *K, L,* and *M* series. No attempt has been made to plot the energy levels to scale.

FIG. 1. Qualitative terminology diagram from [7, p. 630].

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, or 3 shell is called a K, L, or M x ray, respectively. These characteristic energies are unique to individual elements.

X-ray fluorescence *via* 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.

Emission of photons *via* excited nuclei decay:

One example of this process is the decay of the excited nucleus of ^{133}Ce created by the beta decay (K-electron capture) of ^{133}Ba. In this case, both the nucleus and the electrons are left in an excited state of ^{133}Ce, resulting in the emission of nuclear gamma rays as the nucleus relaxes to its ground state and the emission of a 31 keV cesium Kα x ray as the atomic electrons relax to their ground state.

Annihilation of electron-positron pairs: Some unstable nuclei (*e.g.* ^{22}Na) undergo an inverse 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. The ejected positron eventually interacts with an electron in the surrounding material, annihilating

into photons. Such annihilations usually yield two photons which, in the center of mass frame, travel in exactly opposite directions and with each carrying an energy of precisely $m_e c^2$ in accordance with the conservation of momentum and energy.

II.2.   Interactions of X Rays with a Solid State Crystal

An x-ray photon can interact with the germanium crystal used as a detector in this experiment 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 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 of lowered energy which may escape the crystal.

3. Pair creation, if the energy of the incident photon is sufficiently large ($h\nu > 2m_e c^2$). 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, which may be neglected here.

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 then further interact with the crystal.

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 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.

II.3.   Moseley's Law Theory

Moseley discovered that the wave numbers $k \equiv \frac{1}{\lambda}$ of characteristic x-ray lines emitted by the elements under electron bombardment are related to the atomic number Z by equations of the form

$$\sqrt{k} = C(Z - \sigma), \tag{1}$$

where C is a coefficient with units of $\sqrt{\text{length}}$ that depends on the type of x-ray line, and σ is a unitless value that accounts for electron shielding, making $Z - \sigma$ an effective nuclear charge.

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

$$E = hck, \tag{2}$$

where h is Planck's constant and c is the speed of light. In terms of x-ray energies, the Moseley relation reads

$$\sqrt{E} = C'(Z - \sigma). \tag{3}$$

This equation can be used to predict the characteristic x-ray energies for elements as a function of atomic number. Moreover, measurements of photon energies can be used to determine the identity of an unknown material. This is the basis of x-ray spectroscopy.

III.   APPARATUS

Figure 2 is a block diagram of the electronic equipment. The detector is a Canberra model BE2020 high-purity germanium broad energy x-ray detector connected through a preamplifier to an amplifier, and thence to a 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, but is discouraged unless you encounter extremely high count
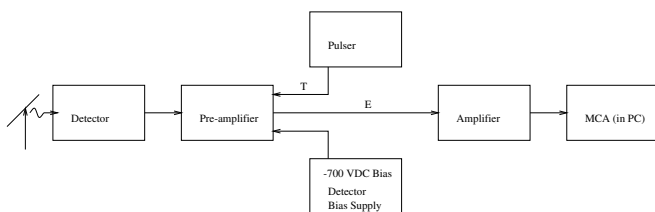
FIG. 2.   Schematic diagram of the circuit arrangement for x-ray spectroscopy, including the Canberra BE2020 detector.

rates.) The MCA sorts the pulses according to their amplitudes and records the number of pulses in each of 2048 amplitude intervals known as "channels" or "bins". A histogram display of these numbers is generated by the MCA and represents the energy spectrum of the detected x rays.

III.1.   Detector

The detector is a single crystal of p-n doped germanium mounted behind a thin carbon fiber window in a vacuum. To reduce thermal noise, it is connected to a copper "cold finger" which dips into liquid nitrogen contained in a large Dewar below the detector. This arrangement conducts heat away from the crystal and keeps the detector at a temperature near 80 K, assuring 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 more than +3000 VDC in order to sweep out any conduction electrons that appear. The "depletion zone" in the biased crystal is effectively an insulator. Only photoelectrons ejected from germanium atoms excited by incident x rays (or as a result of rare thermal excitations) will conduct, thus producing a signal. Around 1.8 eV is needed on average to produce an electron-hole pair in a germanium crystal.

III.2.   Starting Up

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 (0–10 V).

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.

Turn on the NIM-bin power supply, the PC, and the oscilloscope. Connect the amplifier output to the MCA and the oscilloscope. Turn on the high voltage supply and gradually apply the bias voltage of about +3000 V while monitoring the detector output on the oscilloscope. Be sure you apply a positive bias voltage; a negative high voltage bias will damage the detector.

Place a ^{22}Na source a few inches in front of the Ge detector window (The windows is made of very thin carbon fiber. 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 511 keV line appears on the oscilloscope as a concentration of pulses with amplitudes near 5 V. Run the MCA control software called MAESTRO FOR WINDOWS from the desktop. Accumulate a spectrum with the MCA, and adjust the gain so that the ^{22}Na signal appears as a line in the middle of the display. You may have to cut out noise by suppressing the lowest MCA channels. Then place the ^{133}Ba gamma-ray calibration source in the front of the detector window. Check the linearity of the MCA channels from the energy of the known lines. Calibrate the MCA by determining the change in energy per channel. Make sure to recalibrate the MCA whenever you change the amplifier gain. (In fact, recalibrating often throughout the experiment, at least on the ^{22}Na 511 keV line, is a good idea.)

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

IV.   MEASUREMENTS

In this experiment, you will explore the following:

- the fine structure splittings of the K and L shell energy levels;

- the use of x-ray spectroscopy in identification of unknown materials;

- the E versus Z relations (Moseley's law) for the various series of characteristic K and L x-rays (see the original papers in References [8, 9]);

- attenuation cross sections of various metals for x rays of several different energies;

- and a variety of other phenomena.

Analyze the spectra as you take them by using the cursor to determine peak position and the full width at half
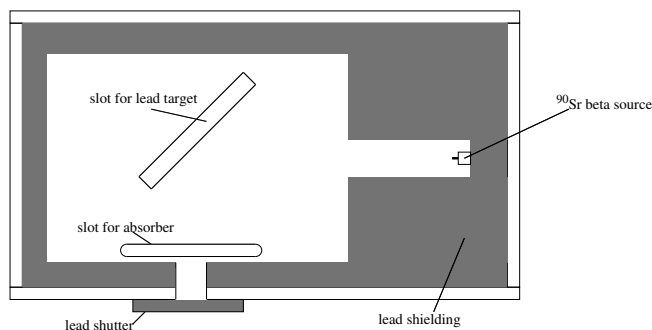
FIG. 3. Arrangement for producing bremsstrahlung x rays by high energy electrons emitted in beta decay of ^{90}Sr and ^{90}Y, and studying the absorption of the x rays by various materials. This is also the arrangement for irradiating samples to produce fluorescent x rays.

maximum (FWHM), and the region of interest (ROI) feature to determine total counts and area under the peaks. You may also save the data file from the MCA for further analysis. As always, do *not* leave simple analysis for after the conclusion of your lab session. Plot simple relations among data as you acquire them to confirm that the experiment is proceeding according to expectations. Record pertinent details about all saved data files in your notebook.

IV.1.   Production of Bremsstrahlung and Characteristic Line Radiation.

Place the ^{90}Sr source (a source of high energy beta particles) so that the hole is facing the germanium detector. Observe the spectrum of pulses with nothing in the 45° slot (see Figure 3). Then put a thin (1/4 inch 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. The most prominent peaks are probably the K lines. Smaller peaks may be L lines or background radiation from weak radioactivity in the room. Identify the energy (with an error estimate) of the high-energy cutoff of the Bremsstrahlung spectrum. This should correspond to the maximum energy of the incident electrons.

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 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 (about 1 mm) layers of plastic are inserted between the window and the detector, or by deflecting the electrons with a strong permanent magnet.

IV.2.   X-ray Induced Fluorescence

Measure the fluorescent radiation emitted by different target materials when they are irradiated by x rays from the ^{241}Am or the ^{90}Sr source. Arrange the geometry 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. What is the lowest energy K line you are able to detect? The highest? What are the limiting factors?

Place an object of unknown composition in front of the x-ray source. There are many objects of unknown composition provided for this experiment. Record the spectra for these unknown materials, and identify locations of the peaks to compare them with known values.

IV.3.   Moseley's Law

Adjust the gain so that the K lines of lead are at the far right end of the MCA histogram and record their positions. The variable x-ray source used in this portion of the experiment (Amersham AMC.2084) is detailed in Figure 4. Its emission characteristics are detailed in Table III.

TABLE III. X-ray energies produced by Amersham variable x-ray source. From Data Sheet 11196.

Target	Energy[a] (keV)		Photon yield[b]
	Kα	Kβ	(sec^{-1}sr^{-1})
Cu	8.04	8.91	2,500
Rb	13.37	14.97	8,800
Mo	17.44	19.63	24,000
Ag	22.10	24.99	38,000
Ba	32.06	36.55	46,000
Tb	44.23	50.65	76,000

[a] weighted mean energies
[b] the photon yield was determined using a high resolution Si(Li) x-ray spectrometer; the photon output is highly collimated limiting emission to about 0.5 steradians.

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.
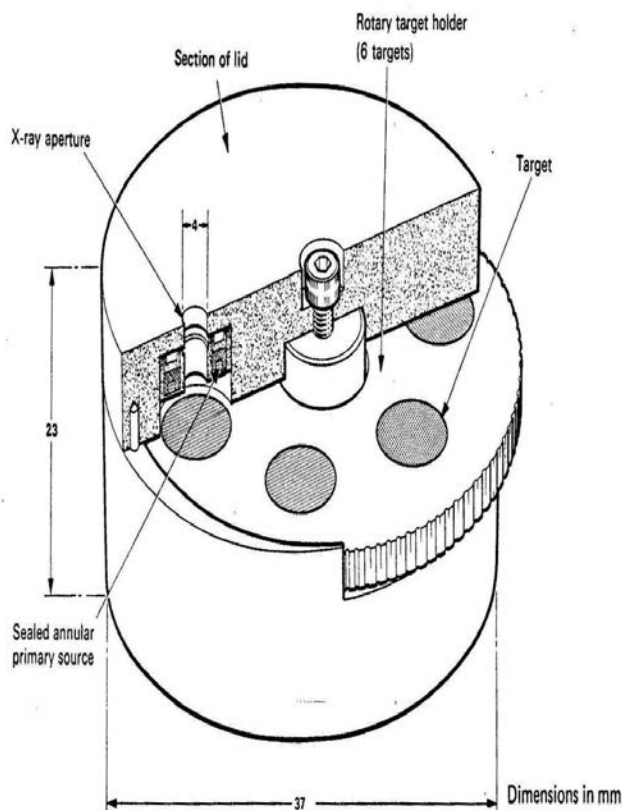
FIG. 4. Diagram of the Amersham variable energy x-ray source. The primary source is 10 mCi of americium-241 ($\tau_{1/2}$ = 433 yr), consisting of a ceramic active component in a welded stainless steel capsule, with integral tungsten alloy rear shielding. The maximum surface dose rate (excluding emission aperture where the dose rate will vary with the target in use) is less than 0.1 mR/h. The principal alpha energies from Am-241 are 5.442 MeV(12.5%) and 5.484 MeV(85.2%). Gamma energies are 59.5 keV (35.3%). Also emitted are some neptunium L x-rays with energies between 11.9–22.2 keV.

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−L and K−M 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 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 end of the display. Note that due to the plastic shielding on the detector, it will be difficult to measure energies below 10 keV. If you feel the need to remove the plastic cover, please talk to an instructor.

IV.4.   Attenuation Coefficients

Measure the attenuation 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 a source of monoenergetic x rays and the detector. (The Amersham variable x-ray source is a convenient source of monochromatic x-rays with energies in the range from 6 keV to about 60 keV: see Figure 4. The gamma ray calibration sources provide monochromatic photons up to 1.3 MeV.)

A typical measurement might be carried out as follows. Place the Amersham howitzer about 10 cm from the detector with the dial turned to Ag. Measure the rate of pulses in the silver K−L and K−M lines using the facilities of the MCA. Place a foil of metal with measured thickness between the source and the detector, as close as possible to the source. Measure the reduced count 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. Repeat this measurement for different metals. If time permits, change the Amersham setting and check the count rate at different photon energies as well.

IV.5.   Emission of Nuclear Gamma Rays and Characteristic X Rays

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 Reference [4] identify as many of its features as you can.

IV.6. e^+e^- Annihilation Radiation

Place the ^{22}Na gamma-ray calibration source near the germanium detector. Turn the gain down by steps until the spectrum of pulses produced by photons with energies in the energy range from 0–1.5 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 germanium 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. With sufficient statistics you may see a tiny blip in the spectrum near 0.511 MeV. How do you account for that?

IV.7.   Challenge Projects

1. Place a ^{137}Cs calibration source close to the detector window and reduce the amplifier gain so as to place the needle-sharp 661.63 keV gamma-ray line near the right-hand side of the MCA display. Don't be confused by the higher level reset pulse from the detector preamplifier. 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.

3. 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.

4. Using the Ag source in the Amersham source, compare the absorption cross sections of cadmium and palladium for the K−L and K−M 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 a ^{55}Fe source.

5. 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 the details of the spectrum in the range of energies around the K−L (Kα) line of molybdenum. Observe the K−L absorption line, and explain how its place in the spectrum is related to the K−L line.

V.   ANALYSIS

V.1.   Bremsstrahlung Analysis

Using the K−L 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)?

V.2.   Fluorescence Analysis

Try to identify all the lines found in the various x-ray spectra. Use the calibration to identify the energies of these lines. Compare these energies to the characteristic energies of the metal from which they were recorded. Then check the energies from the unknown metals. Use the measured characteristic x-ray energies and count rates to identify the percent composition of the metal.

V.3.   Moseley's Law Analysis

The essential features of Moseley's law are 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−L$_3$, K−N$_3$, L−M, *etc.*), and determine the values of C_n and σ in each case.

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 germanium K lines from data on the identified escape peaks.

2. Determine the ratios of the intensities of the Kα_1 and Kα_2 lines and compare with the theoretical expectations based on consideration of the statistical weights of the parent L$_3$ and L$_2$ states (see Reference [7, pp. 646–655]).

3. According to an approximate treatment of the spin-orbit interaction (see Reference [7, p. 606]), the doublet separation in energy should vary with Z as $(Z - \sigma)^4$. Compare this prediction with your data.

4. *Theoretical challenge*: For the case of Tb, verify that the magnitude of the spin-orbit splitting is that given by perturbation theory. 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?

V.4.   Attenuation Coefficients Analysis

Plot the natural log of the count rate against the thickness of the attenuator. Check whether the data conform to the formula for exponential attenuation, namely

$$I(x) = I_0 e^{-\mu x} \Rightarrow \ln\left[\frac{I(x)}{I_0}\right] = -\mu x, \qquad (4)$$

where x is the thickness and μ is a constant called the attenuation coefficient. Dividing μ by the density of the material ρ gives a more useful quantity known as the mass attenuation coefficient.

Fit a straight line to the log plot. 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).

POSSIBLE TOPICS FOR ORAL EXAM

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

2. Compton scattering

3. Classical theory of the Thomson scattering cross section of the electron, *e.g.* Reference [10]

4. The bremsstrahlung spectrum, *e.g.* Reference [11]

5. Attenuation of an x-ray beam in matter, *e.g.* Reference [10]

6. The theory of the high-purity germanium detector, *e.g.* Reference [2]

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Appendix A: Historical Elements of X-Ray Physics

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 1930s 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. Today, x rays are of critical importance in the fields of medical imaging; material science, for determining both composition and structure; transportation security, for example airport baggage inspection; microscopes with suboptical resolution; astrophysics and cosmology; crystallography, such as the famous example of Rosalind Franklin's discovery of the double helix structure of DNA; and observing fast reactions with synchrotron radiation.

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 an airport baggage inspection system, employs a vacuum tube in which electrons emitted from a filament-heated cathode are accelerated by an electric field supported by a high-voltage (say, 50 kV) 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.

After Röntgen's 1895 discovery of x rays, the most important landmarks in the field's subsequent development included 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, Siegbahn's studies in x-ray spectroscopy [12] and Compton's discovery of the quantum character of the scattering of x rays from free electrons [7, 13, 14].

Röntgen initially thought — tentatively and incorrectly — that the new rays he had discovered 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.

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