ELECTROMAGNETIC INTERACTIONS IN MATTER

The purpose of this laboratory session is to demonstrate various electromagnetic interactions in matter. First, you will learn how x-rays are produced and used in the determination of interatomic distances. By diffracting x-rays from a crystal of known atomic spacing you will determine the wavelength and energy of the characteristic x-ray radiation emitted from copper. From this information you will identify an unknown crystal. Next, you will familiarize yourself with the instrumentation used to analyze the high-energy emission spectra of unstable isotopes. Finally, you will analyze the structure of emission spectra of various radioactive isotopes to determine the physical processes that are taking place.

Part I
Bragg Diffraction with X-rays (Background)

X-rays are a high-energy form of electromagnetic radiation that has wavelengths ~0.1 nm ($10^{-9}$ m). A typical diffraction grating used with for visible light has ~5000 gratings/cm. This corresponds to a line spacing of 2000 nm. Recall that the condition for constructive interference of light of wavelength $\lambda$ on a grating with line spacing $d$, is

$$m\lambda = d\sin \theta$$

where $m$ is the “order” of the diffraction maximum and $\theta$ is the diffraction angle.

Question: Using $m\lambda = d\sin \theta$, calculate the angle that the first order diffraction of a 0.1 nm x-ray would appear if using a transmission diffraction grating with a $d$-spacing of 2000 nm. Is this practical? If so, how so? If not, why not?

[ANSWER ON A SEPARATE PAGE AND SUBMIT WITH YOUR HOMEWORK.]

By now, you have likely realized that a diffraction grating having a line spacing that is approximately equal to the wavelength of the electromagnetic radiation is more desirable. In 1912, German physicist Max von Laue recognized that a crystalline solid could be used as a natural diffraction grating since the x-ray wavelengths are about equal to atomic diameters. A crystal has a periodic array of atoms that repeats itself. When x-rays enter the crystal, they get scattered in all different directions. Certain directions can give rise to constructive interference while others give rise to destructive interference. An oversimplified picture of the process is depicted in Fig. 1 on the next page.
For the situation depicted in Fig. 1, constructive interference occurs when the path difference between the rays is an integer number of wavelengths. As seen in Fig. 2 below this condition is given by

$$2d\sin\theta = m\lambda,$$

where $d$ is the spacing between the crystal planes, $\theta$ is angle the incoming (and outgoing) x-rays make relative to the surface of the crystal, and $\lambda$ is the wavelength of the x-rays. The integer $m$ is the number of additional wavelengths that Ray 2 travels than Ray 1.

The expression above is known as the Bragg condition. In 1915, British physicist William Bragg shared the Nobel Prize in Physics with his father for their work using x-rays to study crystal structure.

---

In x-ray optics, the angle of incidence is measured with respect to the surface of the crystal (unlike geometrical optics where the angle is measured relative to the normal).
A schematic of the x-ray diffractometer that you will use is shown in Fig. 3. The apparatus is a small tabletop unit that consists of the x-ray producing tube, a sample holder, and a Geiger-Muller tube to detect the scattered x-rays. The angle Vernier rotates the Geiger tube at twice the angle that the crystal moves. This is so that the Bragg condition (Fig. 2) is maintained for any position of the detector. (Recall that the Bragg condition requires that the angle that the incident x-rays make with the sample equals the angle that the detector makes with the sample.)

![Diagram of x-ray diffractometer](image)

Fig. 3: Overhead view of the x-ray diffractometer. X-rays generated in the tube are directed toward a sample making an angle $\theta$ to the surface. The 2-to-1 gear ratio moves the detector through an angle $2\theta$ so that the Bragg condition is always maintained.

The x-rays are produced inside the x-ray tube by bombarding a copper pellet with a beam of highly energetic electrons. The electron beam is produced essentially “boiling off” electrons from a hot filament (a process called thermionic emission) and then accelerating them by a high voltage (~10 kV) toward the copper pellet. Upon striking their target, the energetic electrons excite the copper atoms in the pellet that in turn emit x-rays when the excited atoms return to their ground state. The distinct wavelengths of these x-rays are a characteristic of the copper atoms resulting from the differences between distinct energy levels with the copper atoms.

X-rays are also produced through another process known as Bremsstrahlung (or “braking” radiation). This process produces a continuous spectrum of wavelengths as a result of the incoming electrons being slowed by collisions with the atoms in the target. (Recall that whenever a charged particle is accelerated, it emits electromagnetic radiation.) The overall intensity of the radiation as a function of wavelength from the copper target will contain both the distinct wavelengths characteristic of the copper along with the continuous Bremsstrahlung spectrum and look something like the graph shown in Fig. 4 on the next page. From the Bragg condition, it can be seen that the minimum angle corresponds to the maximum kinetic energy the electrons acquire as they are accelerated.
through by the voltage between the filament and the copper target. The accelerating voltage is set to 30 keV for this activity.

![Graph](image)

Fig. 4: Typical x-ray spectrum produced from the diffractometer. Note that the overall intensity distribution of the x-ray spectrum emitted by the copper target consists of the continuous Bremstrahlung distribution along with the discrete peaks corresponding the atomic transitions within the copper atoms.

As mentioned above, the discrete peaks in the x-ray spectrum are due to the electromagnetic radiation emitted when electrons of higher atomic levels cascade back down to fill the lower vacancies created by the bombarding electrons. The energy of the emitted radiation corresponds the energy difference between the levels. In atomic physics, the lowest electron shell is referred to as the $K$-shell. The higher shells are designated alphabetically after “$K$.” That is, the second energy level is called the $L$-shell, the third is the $M$-shell, and so on. An energy level diagram is shown in Fig. 5.

![Diagram](image)

Fig. 5: Energy level diagram (not to scale) showing the 3 lowest shells of a multi-electron atom.

As shown in Fig. 5, when an electron from the L-shell drops to fill the vacancy in the K-shell, the characteristic x-ray is called $K$-alpha ($K_{\alpha}$) radiation. When the transition is from the M-shell to the K-shell, the radiation is called $K$-beta ($K_{\beta}$) radiation.
Questions: Note the energy level diagram shown in Fig. 5. There are also electron transitions from M-shell to the L-shell. This produces what is referred to as $L_\alpha$ radiation. Based on this pattern, what would you expect the radiation resulting from an electron transition from the fourth energy (N-shell) to the L-shell to be called? What about radiation from the N-shell to the K-shell?

[ANSWER ON A SEPARATE PAGE AND SUBMIT WITH YOUR HOMEWORK.]

While the x-rays from the copper pellet are emitted in wide range of directions, the only x-rays that actually leave the tube are those that are directed toward the sample holder by passing through a small vertical slit in front of the tube. The walls of the x-ray tube stop the rest. To prevent a user from being exposed to the x-rays emitted from the tube, the unit has a transparent cover infused with lead and a metal beam stop that is safety interlocked. No x-rays can penetrate the lid. This can be verified by moving a Geiger tube around the perimeter of the unit while the x-ray tube is active and noting that no counts above the normal background are detected. Furthermore, the lid cannot be opened while the x-ray tube is energized. Any attempt to do so will automatically disengage the high voltage that generates the x-rays.

Procedure

Your group will need the following materials/equipment for this part:
- 1 Tel-Atomic tabletop x-ray diffractometer (with motor drive)
- 1 computer with Tel-Atomic software installed and appropriate cabling
- 3 alkali-halide crystals: 1 lithium fluoride and 2 unknowns
- plastic gloves and tweezers (to handle the crystals)
- 1 Geiger tube with external counter/scaler

1. Examine the diffractometer unit. To open the lid, slide the lid to the right and then lift it up. Look at—but do not touch the x-ray tube. (There is no danger of x-rays, but the tube has been aligned to maintain the Bragg condition. Touching it can knock the tube out of alignment.) You should be able to see the copper target inside the x-ray tube. The blue box to the left of the sample holder is the motor drive unit that will automatically sweep through the angles that you select for your scans.

2. Plug in the external scaler/counter and connect the Geiger tube to the scaler/counter BNC connection labeled “GM tube.”

3. Start the motion analysis program on the computer by opening the Tel-Atomic alias on the computer desktop.
4. Once you have successfully opened the proper file, the computer will display a graph of “Counts vs. Angle”. Note that the units for the angle axis and time axis are degrees and seconds, respectively.

5. In the lower right corner of the data collection window, click on the Set Up button. Note the angular position of the Geiger tuber by reading the Vernier scale on the movable detector arm. (Note the fine scale reads in increments of 10 arc minutes, but the Tel-Atomic program reads in decimal units of degrees.) Click the up/down button in the window to tell the program the current location of the detector. This is best done when the detector arm is location exactly on a degree marking. (Remember this angle corresponds to $2\theta$.) Save this setting.

6. Set the minimum and maximum angular range to 15.0° and 105.0°, respectively. Set the Dwell Time to 2.0 s and the Angular Resolution to 0.20°.

7. Set the voltage for the Geiger tube to 500 V by clicking on the arrows next to the Detector HV display. Then activate the high voltage by clicking on the HV button.

**Important Note:** The oils in your skin will degrade the alkali-halide crystals if they are handled with bare hands. Be sure to wear the plastic gloves when mounting and removing the crystals. Also, the crystals are extremely brittle (and expensive!) Be sure to handle them with extreme care and DO NOT DROP THEM!

8. Place the lithium fluoride (LiF) crystal vertically in the center holder. For best results, be sure that the smooth shiny side is facing to the left against the center post and the rough dull side is facing to the right (away from the drive unit).

9. Check that the motor drive is receiving power, properly connected to the computer with the USB cable.

10. Carefully close the lid of the diffractometer and slide the interlock to the center position. Turn the white knob on the diffractometer to the 50-min mark. This energizes the filament which produces the electrons.

11. Press the “X-rays” button to activate the high voltage that accelerates the electrons into the copper target. This accelerating potential has been pre-set to 20 kV.

12. To start the data collection, click the start button in the lower left corner of the data collection window.

13. Use the cursor on the graph to identify the angles of the peaks and the minimum angle where the non-zero counts start.

14. Save/print the Counts vs. $2\theta$ graph for further analysis.

**Another Important Note:** The unit should sweep through angles to the 15.0° mark and then start collecting. Watch carefully. If the arm appears to move to an angle less that 13.0°, stop the data collection and inform your instructor. This is to prevent damage to the unit if the stepping motor tries to ram the detector arm into the interlock post.

For the nearly 500 data points collected at 2.0-s count times, the data collection should take about 16 minutes.
15. After completing a satisfactory run, turn off the x-rays by sliding the lid to the right. Open the lid and repeat Steps 7-12 with an unknown crystal. Be sure to carefully place the LiF crystal back into its protective case.

**Checkpoint:** Consult with your instructor before proceeding. **Instructor’s OK:**

---

**Part II**

**Gamma Spectrum Analysis**

**(Background)**

The gamma ray spectroscopy arrangement can be explained as follows: a gamma source is placed near a sodium iodide crystal doped with thallium. The NaI crystal has a high density and thus provides a high probability that a gamma ($\gamma$) ray entering the crystal will be absorbed. The crystal contains thallium (Tl) impurities (~1%) that form localized energy levels just below the energy required to boost an electron from the valence band to the conduction band of the crystal. An electron knocked into the conduction band typically returns to the valence band in a time of $\sim 10^{-8}$ s with the emission of a photon whose energy is equal to the band gap energy. The Tl impurities trap the electrons and keep them from returning to the valence band for up $\sim 1$ ms as shown in Fig. 6.

![Diagram](attachment:image.png)

**Fig 6:** An electron in the valence band is boosted into the conduction band. The thallium impurities create trapping levels that delay the electron’s return to the valence band. When the electron returns to the valence band a photon whose energy equals that of the band gap energy is emitted.

Upon returning to the ground state in the valence band, a photon is emitted. Since the band gap energy is on the order of a couple of eV, the emitted photon is that of visible light. These photons pass through the (transparent) NaI crystal into a photomultiplier tube where they strike a photocathode. The photocathode will emit electrons (recall the photoelectric effect) whose number is proportional to the number of photons striking it. Since the number of photons striking the photocathode is proportional to the energy of gamma ray, the number of photoejected electrons will be proportional the energy of the gamma ray.

The photoejected electrons are then accelerated by a positive voltage toward the first of series of about ten dynodes. Each dynode has a positive potential difference with respect to the previous one. As an electron accelerates toward the first dynode, it gains enough kinetic energy to knock additional electrons from that dynode. These electrons are then accelerated toward the next dynode, which knock out still more electrons, as so on. The process continues until the cascade of electron reaches the anode where they produce measureable current pulses. The current then goes to a linear amplifier and finally to a
A multichannel analyzer will bin the resulting voltage pulses into specific channels. This use of the multichannel analyzer is referred to as pulse height analysis. Peaks in various channels correspond to γ-rays of particular energies being detected.

I. Detector Resolution

Resolution is a measure of the detector’s ability to distinguish γ-rays of similar energies. A rough determination of the resolution of the detector can be found using:

\[ R(\%) = \frac{FWHM(\Delta \text{Channels})}{\text{Centroid Channel #}} \times 100\%, \]

where FWHM is called the “Full Width at Half Maximum,” and is found to reasonable accuracy by finding the two channels on each side of the peak that have the number of counts closest to \( \frac{1}{2} \) of the maximum number of counts in the peak. The “Centroid Channel #” is the channel that corresponds to the location of the maximum count number for that peak.

In this part, you will acquire and analyze the gamma spectra of various radioactive isotopes. In particular you will examine the spectra of \(^{137}\text{Cs}, ^{60}\text{Co}, ^{54}\text{Mn}, \) and \(^{22}\text{Na}\) while you determine the energy dependence of the detector resolution.

**Procedure**

1. Place one of the sources on the tray and insert the tray in the sample holder so that it is as close as possible to the photomultiplier tube.
2. Click start button and collect a spectrum until there are about 2000 counts in a peak near the center of the screen. (Note that the y-axis is scaled logarithmically.) Then click the stop button.
3. Drag the cursor along the data to identify the channels (and energies) associated with each peak. Record these in your own data table.
4. Determine which peak(s) correspond to photoemission peak (See chart under “Total absorption photoemission peak” on the next page.) Determine the resolution of the detector for that energy by recording the centroid channel and the FWHM for the total absorption photoemission peak.
5. Check with your instructor that you have a quality spectrum. Upon instructor approval, print the gamma spectrum for further analysis.
6. Remove the source, return to its case, and repeat these steps for the other sources.

**Checkpoint:** Consult with your instructor before proceeding. **Instructor’s OK:**  

II. Typical Gamma Ray Processes
The information on the following pages is to provide you with the information necessary to identify the various processes taking place in a typical gamma spectrum. As you will see, there are several peaks and valleys that are observed. However, not all of the features observed are due to radioactive decay directly. Many of these features are the result of secondary processes such as electron photoejection and Compton scattering. Your task will be to identify as many of these additional processes as you can.
Total absorption photoemission peak:

When a radioactive source decays, the daughter nucleus is often in an energetically excited state. When the nucleus de-excites, electromagnetic energy corresponding the energy difference between the nuclear energy levels is radiated. (Because these are nuclear transitions, the energy of this radiation is much higher than those involving electron transitions.) The nuclear radiation emitted tends to be in the $\gamma$-ray regime of the electromagnetic spectrum. Different $\gamma$-emitters have different characteristic energies for their photoemission peaks. Below is a table of the photoemission energies of various sources.

<table>
<thead>
<tr>
<th>Isotope $^{A}$X</th>
<th>Photoemission Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{137}$Cs</td>
<td>662</td>
</tr>
<tr>
<td>$^{54}$Mn</td>
<td>835</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>1275</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>1173 and 1332</td>
</tr>
</tbody>
</table>

Internal conversion peak:

The $^{137}$Cs nucleus decays by $\beta^{-}$-emission into an excited state of $^{137}$Ba. The $^{137}$Ba nucleus de-excites and can either emit a 662 keV photon or give up its energy to a core (usually a $K$-shell) electron. When a higher shell electron (usually from the $L$-shell) drops down to fill the vacancy, a characteristic 33 keV x-ray is emitted. When these photons enter the detector, a strong signal at 33 keV is observed.

Pb x-ray peak:

Often, the scintillation counter is surrounded by a thick lead (Pb) barrier to shield the detector from stray background radiation. The $\gamma$-rays emitted from the source can have a photoelectric interaction with the lead shield that ejects a core ($K$-shell) electron. When an electron from the $L$-shell drops to fill the $K$-shell vacancy, a 75 keV photon is emitted. Many of these photons enter the detector where they are recorded.

Since this peak is due to photoelectric interactions with the lead shield surrounding the detector, it will generally appear for any radioactive source that emits photons greater than 75 keV.
Compton backscatter peak:

This peak is the result of source $\gamma$-rays that undergo $180^\circ$ Compton interactions with the surroundings opposite the detector and then enter the detector. Recall that the wavelength shift in the Compton effect is given by

$$\lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \theta),$$

where $\lambda'$ is the wavelength of the Compton shifted photon, $\lambda$ is the wavelength of the incident photon, $h$ is Planck’s constant, $m_e$ is the electron mass, $c$ is the speed of light, and $\theta$ is the angle at which the scattered photon travels with respect to the incident photon. For Compton backscattering, $\theta = 180^\circ$.

Compton edge:

A typical $\gamma$-ray spectrum will show a sudden drop-off in counts at energies just below a peak. The energy where this “edge” occurs just before the drop-off corresponds to the energy of the recoiling electrons after a Compton backscattering. This energy plus the energy of the $180^\circ$ backscattered photon equals the photon energy of the original $\gamma$-ray.

The “dip” seen at energies just above the Compton edge is referred to as the Compton valley. This valley is due to photons that interact with the detector via the Compton effect, then scatter out of the detector never to be detected.

Annihilation peak:

These peaks are found in $\beta^+$-emitters. The positron ejected from the decaying nucleus quickly meets an electron where the electron and positron annihilate each other and produce two equal photons whose energies equal the rest mass energies of the annihilating pair. Both the electron and the positron have rest mass energies of 511 keV. Typically, one of these photons enters the detector and the other moves in the opposite direction and is not detected. (A peak at 511 keV is the signature of a $\beta^+$-emitter.)

Sum peaks:

In some instances, two principle $\gamma$-rays entering the detector are detected at the same time. When this occurs, the detector cannot distinguish between two separate $\gamma$-rays or a single $\gamma$-ray having the energy equal to the sum of the two individual $\gamma$-rays. As a result there will often be a small peak at that sum energy. This is not a true $\gamma$-ray energy emitted from the source, but rather an anomaly that occurs within the detector.

Use the information above to identify the feature in the spectra of the radioisotopes.

**Checkpoint:** Consult with you instructor before exiting the lab. **Instructor’s OK:**
Cesium-137

<table>
<thead>
<tr>
<th>Feature</th>
<th>Measured Energy (keV)</th>
<th>Theoretical Energy (keV)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Manganese-54

<table>
<thead>
<tr>
<th>Feature</th>
<th>Measured Energy (keV)</th>
<th>Theoretical Energy (keV)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sodium-22

<table>
<thead>
<tr>
<th>Feature</th>
<th>Measured Energy (keV)</th>
<th>Theoretical Energy (keV)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cobalt-60

<table>
<thead>
<tr>
<th>Feature</th>
<th>Measured Energy (keV)</th>
<th>Theoretical Energy (keV)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>