

1. Atomic X-ray Spectra

Purpose:

Examine the energy of atomic X-ray emission lines for a set of elements and study their absorption behavior. In particular, you will verify Moseley's law, spin-orbit splitting, exponential attenuation with distance and the energy-dependence of absorption for Zr.

Background Reading:

Brehm and Mullin pp. 161-165 (Moseley's law) and 457-464 (selection rules and spin-orbit splitting). These pages are an absolute minimum requirement for the theoretical background for this experiment.

Skills/Concepts:

Multi-channel analyzer (MCA); Counting statistics (\sqrt{N}); Fitting overlapped peaks.

Precautions:

The Ge detector MUST be cooled for several hours before operating. Applying HV to a non-cooled detector will destroy it. In addition, the HV must be changed slowly ($\sim 10\text{V/sec}$) to allow the crystal to accommodate. Do not disturb the plastic cap on the front of the detector, which protects a thin beryllium window. The window is easily punctured, which would destroy the detector and possibly release highly toxic Beryllium. The X-ray source is small and round and is an excellent gravity detector - do not drop it. It should be clamped in the ring-stand such that the opening points forward but the dial is free and visible.

Theory

In the Bohr model for a "one-electron atom" with atomic number Z , the energy of X-rays emitted when an electron drops from "m" to "n" levels is given by

$$\Delta E_{\text{bohr}} = E_B Z^2 (1/m^2 - 1/n^2), \quad \text{Eq. 1}$$

where $E_B = 13.6\text{eV}$. Standard nomenclature uses K, L, M for $n = 1, 2, 3$ and α, β for $m = 2, 3$, etc. Moseley's law shows that X-ray energies vary with Z as

$$E(Z) = C (Z - \sigma)^2, \quad \text{Eq. 2}$$

where Z is the atomic number, while C and σ are constants for a given series (m, n values). This result established that the atomic number, nuclear charge and electron count for a neutral atom are all given by Z . X-ray lines may exhibit spin-orbit splitting due to the interaction of electron spin with orbital motion. This results in a closely-spaced pair (multiplet) of lines with an energy separation that scales as

$$\Delta E_{\text{so}} \sim Z^4. \quad \text{Eq. 3}$$

The intensities of the two components will reflect their "multiplicity".

The attenuation of X-rays as they pass a distance x through matter is given by a simple exponential form,

$$I(x, E_\gamma) = I_0 e^{-x/\lambda} = I_0 e^{-\mu(E_\gamma) \rho x} \quad \text{Eq.4}$$

where ρ is the mass density (6.44 in g/cm³ for Zr). The mass absorption coefficient $\mu(E)$ is strongly energy dependent, and roughly follows a power-law as

$$\mu(E) : E^{-n}, \quad \text{Eq. 5}$$

but with sharp jumps at “absorption edges” (corresponding to $m \rightarrow \infty$ in Eq. 1). The absorption is much stronger for photon energies just above an edge. In addition, there is an important “fine structure” in the energy range of 200eV above the edge (higher kinetic energy), due to interference of the wavefunction of the unbound, escaping electron. This “X-ray absorption fine structure” (EXAFS) can provide important bonding information about the emitting atom. For surface atoms, this method has the intriguing acronym “SEXAFS”.

Counting Statistics (\sqrt{N}).

“Radioactivity” experiments provide perfect examples of count-limited uncertainties, which follow Poisson statistics. For example, suppose you have a signal with a mean value of N counts. If this signal is measured m times, the m values have a standard deviation of \sqrt{N} . Thus, ~68% of the m values will lie within $\pm\sqrt{N}$ of the mean value, N . Note then that the signal to noise ratio (SNR) for such a signal will improve as $N/\sqrt{N} = \sqrt{N}$, thus as the square root of the count-time. Note that there may be a background under the peak, which contributes its own Poisson uncertainty. Ironically, subtracting a background will make the SNR worse!

Part I: Detector calibration and peak fits.

1. Check the LN2 log to see that the dewar has been filled recently (within a few days). The housing should be cool to the touch. Set the HV dial to zero before turning on the NIM crate. Turn on the scope and MCA.
 - Run “HWSuper” to connect instrument to the software:
 - Click “Serial Port”
 - Click “PGT/ANS Com”
 - Click top left Quantum Com, choose 115000 Baud is chosen, click “Update”
 - Should say “communications verified”. Close HWSuper.
 - Start QtmMCA software

Be sure to save all scans in both native and *.txt format, so you can do analysis off-line. Indeed, one person can do “analysis” on a second PC, while the spectra are running.

2. Put the source into position and set the selector for Cu, the lowest energy line. ***Slowly*** (taking about one minute) raise the voltage on the semiconductor detector to -1000V. This can be done in steps of 200V. (Be sure to also turn this supply down ***slowly*** when you finish for the day). Adjust the voltage gain of the amplifier so highest energy line (Am) appears near the top of the MCA bin range. Look at the pulses on the scope – they should have a maximum peak height of ~8V, since the MCA input range is 10V. Adjust the source distance from the

detector to get a good count rate without saturation (dead time). The full spectrum will show Cu lines as well as the driver line (Am) and possibly other residuals, nicely spread over the MCA bins.

3. Calibrate the detector response (Ch# vs Energy) using the built-in 2-point scheme with Cu K_{α} (8.04keV) and ^{241}Am (59.5keV) lines. Be sure that you have identified the peaks correctly! The MCA should now show a keV scale, which you may use for all further analysis.

Part II: Counting statistics and peak fits

4. Put a strong source in place and begin the MCA acquire. Notice that the spectrum “improves” as the counts accumulate. We can quantify this with a simple experiment: Find the integrated counts for a peak of interest using the ROI tool (shift+drag). Note that the integral depends on the width of integration, so keep the ROI fixed. Now set the acquisition time to 10 sec and run the scan 10 times, recording the integrated value for each trial. Calculate the mean value and standard deviation for these 10 trials. Now take a single scan of 100 sec. Compare the mean value (cps) and uncertainty for these two cases, using \sqrt{N} for the uncertainty of the single long scan.

Part III: Moseley's Law

5. Record spectra for all the targets in the source carousel, using appropriate counting times to resolve the peaks.
6. Fit the peak positions to Moseley's law (Eq. 2). For this purpose, the peak positions can be determined using the MCA ROI tool. Explain the physical meaning of the fit values.
7. Compare the measured energy for the Cu K_{α} line to the Bohr model value.

Part IV: Spin-orbit splitting

Many of the lines show a doublet structure due to spin-orbit splitting. See the sample curve in Figure 1 below. We will study the β doublets, since they have a larger splitting, due to their higher energy.

8. Find the peak positions and intensities using appropriate GA fits. It may be useful to constrain the widths of a spin-orbit pair to be equal.
9. Find the power law (n-value) for spin-orbit splitting (Eq 3).
10. Optional: Use the ^{90}Sr -driven x-ray source with high-Z targets: Ta, Te, Pb. For these elements, the doublet structure should be well-resolved, but the peaks are weak, and will require long counting.

Part V: Absorption edge

In this section, you will measure the absorption edge for Zirconium ($Z=40$, with edge near 18.0 keV) by measuring how it attenuates X-rays with various energies above/below the edge.

1. For each source, record the intensity (cps) for all thickness values that give observable signal. Position the source for maximum count rate w/o “dead-time”.
2. For each source, find the attenuation length λ by fitting to Eq. 4.
3. Find $\mu(E)$ from the set of fits above.
4. Find the magnitude of the jump (ratio of μ above/below) at the edge assuming power-law scaling for $\mu(E)$ above/below the edge (Eq 5).

Questions:

1. Briefly explain the operation of the Ge detector. There is an excellent description in the Canberra manual (copies in lab).
2. What is the physical significance of the constant C and the constant σ in Eq. 2?

Table I Elements in the X-ray carousel source

Element	Z
Cu	29
Rb	37
Mo	42
Ag	47
Ba	56
Tb	65

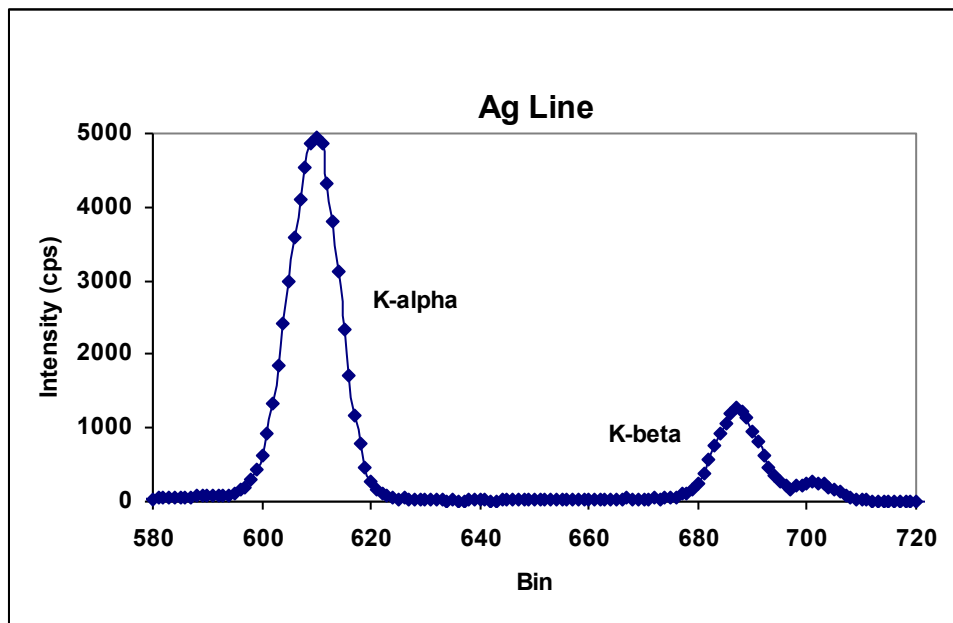


Fig 1 Sample of X-ray line for Ag, showing $K\alpha$ and $K\beta$ doublets. The $K\beta$ doublet is clearly resolved, with the $K\alpha$ doublet is not (it appears as a shoulder).