INTRODUCTION TO ENERGY-DISPERSIVE X-RAY FLUORESCENCE (XRF) – AN ANALYTICAL CHEMISTRY PERSPECTIVE

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WHAT IS XRF?

a. X-ray Fluorescence Spectrometry

b. An elemental analysis technique

c. Another acronym to remember

d. A new scientific gadget to play with

e. The closest thing we have to a tricorder

f. An advanced, highly automated, portable analytical tool that can be used by scientists, lab staff, field investigators, and even non-experts to support their job functions

g. All of the above

TYPICAL APPLICATIONS OF XRF

XRF is currently used in many different disciplines:

Geology
- **Major, precious, trace element analysis**
- **Characterization of rocks, ores, and soils**

Environmental Remediation
- **Pb in paint**
- **Heavy metals in soil (EPA method 6200)**

Recycling
- **Alloy identification**
- **Waste processing**

Miscellaneous
- **Art and archeology**
- **Industrial hygiene**
- **Forensics**

"OWNERSHIP" OF XRF WITHIN ACADEMIA

- Although XRF is a physical phenomena involving the interaction of X-rays with matter, most of the applications of XRF are in areas outside of physics (chemistry, environmental sciences, food and product quality monitoring, etc.)

- Although XRF requires specialized knowledge in chemistry (spectral interpretation, calibration, sample prep, etc.), it is not even mentioned in 99% of undergraduate chemistry programs in the U.S.

- These materials will hopefully encourage wider dissemination and use of XRF in undergraduate chemistry and biochemistry programs and demonstrate its potential as a means for teaching concepts such as spectroscopy, sampling, qualitative and quantitative analysis, and elemental composition in

  - Analytical Chemistry (Quantitative & Instrumental Analysis)
  - Environmental Chemistry
  - Independent student research projects

INTENDED AUDIENCE & OBJECTIVES

These materials were specifically designed for undergraduate chemistry and biochemistry majors

They are also appropriate for novices to the field of XRF and assume only a basic knowledge of chemistry (i.e., general chemistry)

By the end of this presentation, students should understand the following:

1. The basic theory of XRF
2. How to interpret XRF spectra
3. How to do quantitative analysis via XRF
4. Typical applications of XRF

The CSI Syndrome:

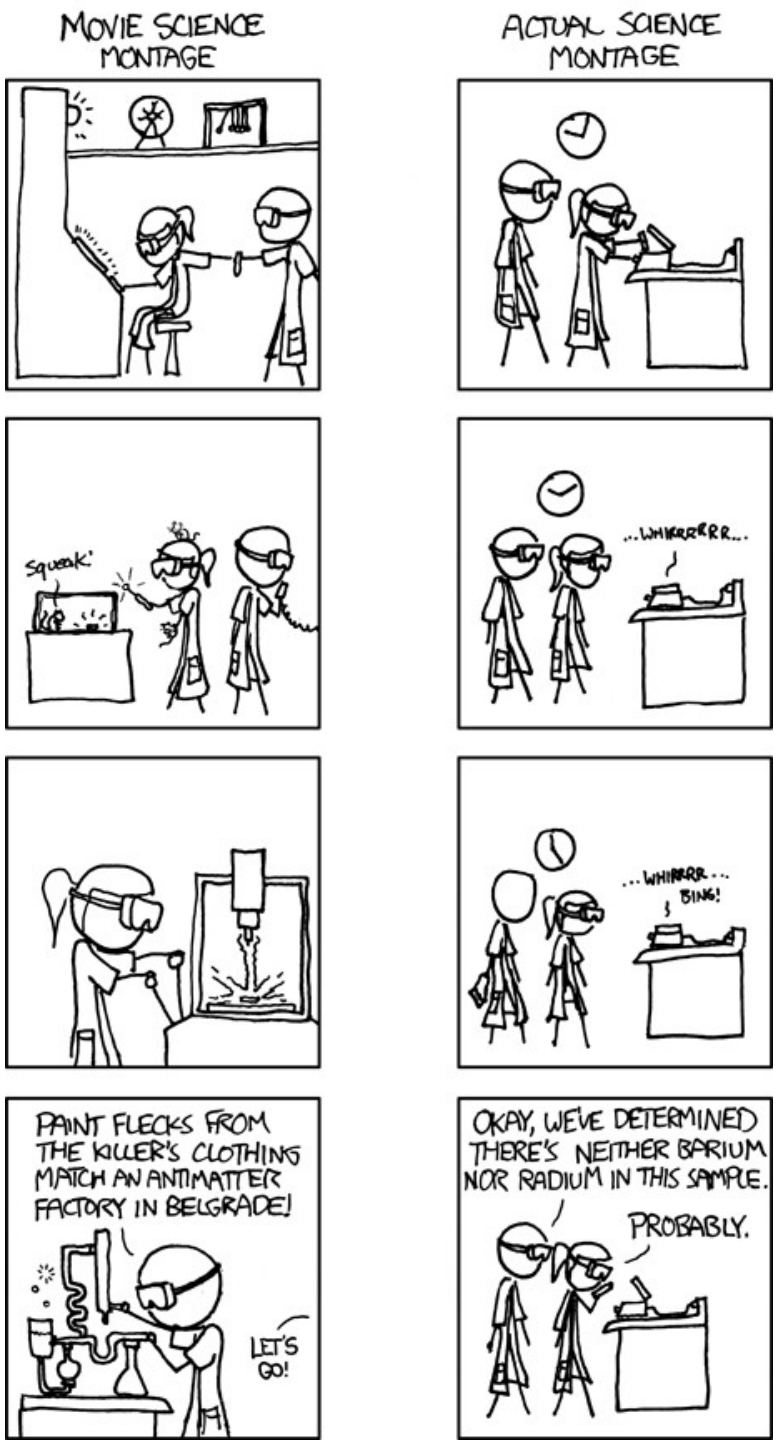
The growing popularity of forensic sciences as evidenced by TV series on this subject has attracted many young people to this discipline

Unfortunately, these shows often trivialize the science and rigor needed to derive reliable results on "real world" samples

Science does not always give yes/no answers (and real world problems are usually not solved in a 60-minute episode)

Forensic science requires careful work and is a lot harder than it looks on TV

Nothing is more useless than an powerful tool that is not used properly



http://www.xkcd.com/

OUTLINE

1. **INTRODUCTION**
   - The electromagnetic spectrum and X-rays
   - Basic theory of XRF and simple XRF spectra
   - Different types of XRF instruments

2. **INTERPRETATION OF XRF SPECTRA**
   - XRF spectra of different elements
   - Limited resolution and overlapping peaks
   - Artifact peaks

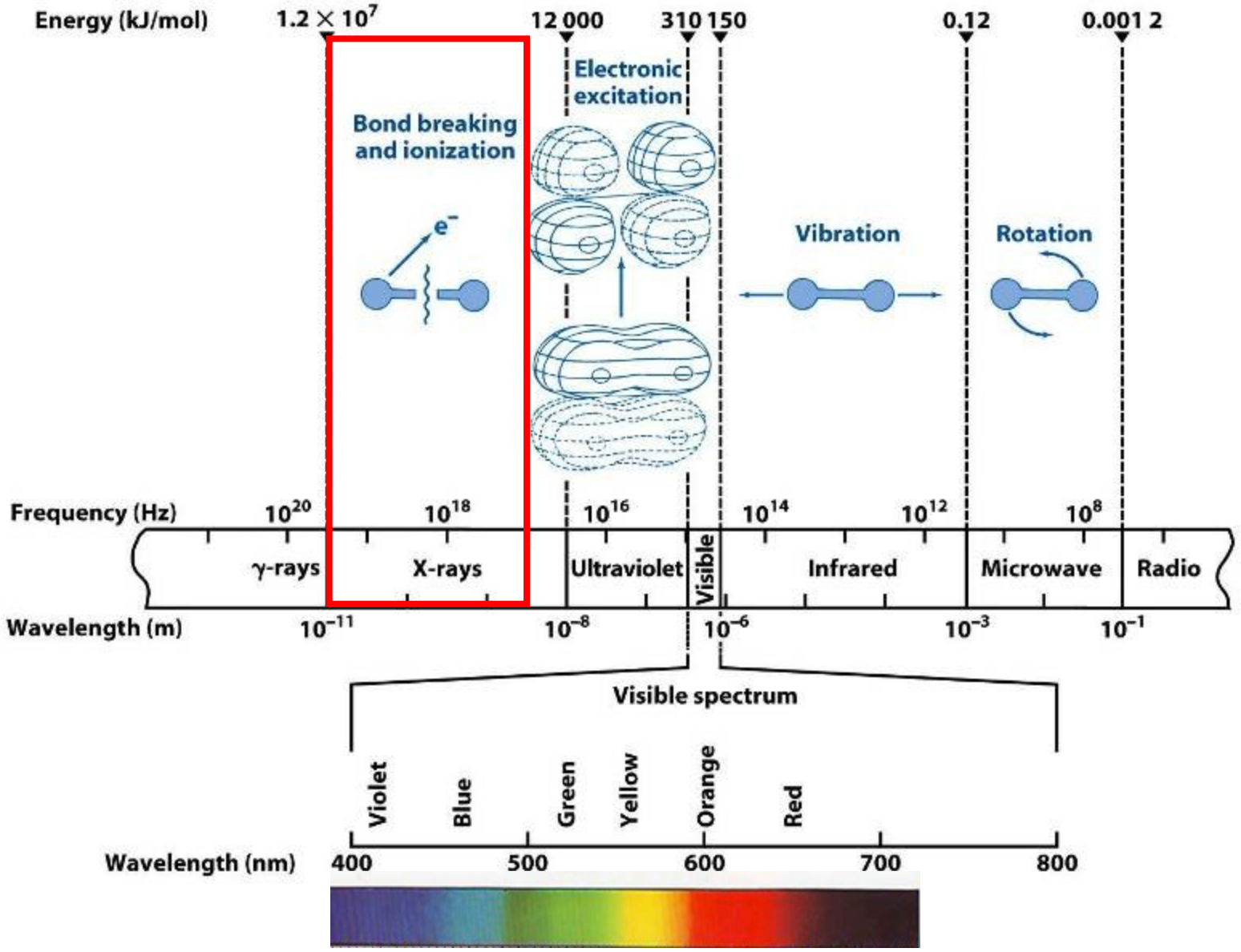
3. **QUALITATIVE AND QUANTITATIVE ANALYSIS**
   - Confirmation of detection of an element
   - Different calibration models
   - Example calibration curves

4. **APPLICATIONS OF XRF**
   - Screening for toxic elements in large numbers of samples
   - Accurate quantitative analysis of target elements in various matrices

5. **CONCLUSIONS**
   - XRF advantages and limitations
   - References and additional reading

THE ELECTROMAGNETIC SPECTRUM

How does light affect molecules and atoms?

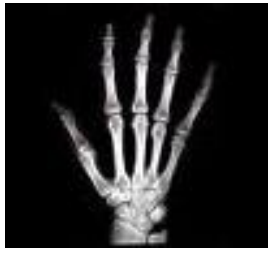


D.C. Harris, Quantitative Chemical Analysis, 7th Ed., Freeman, NY, 2007.

X-RAY INTERACTIONS WITH MATTER

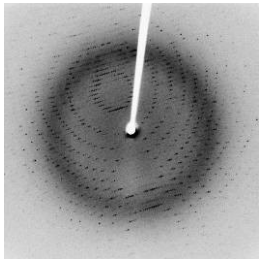
When X-rays encounter matter, they can be:

- **Absorbed or transmitted through the sample**
  (Medical X-Rays – used to see inside materials)



http://www.seawayort.com/hand.htm

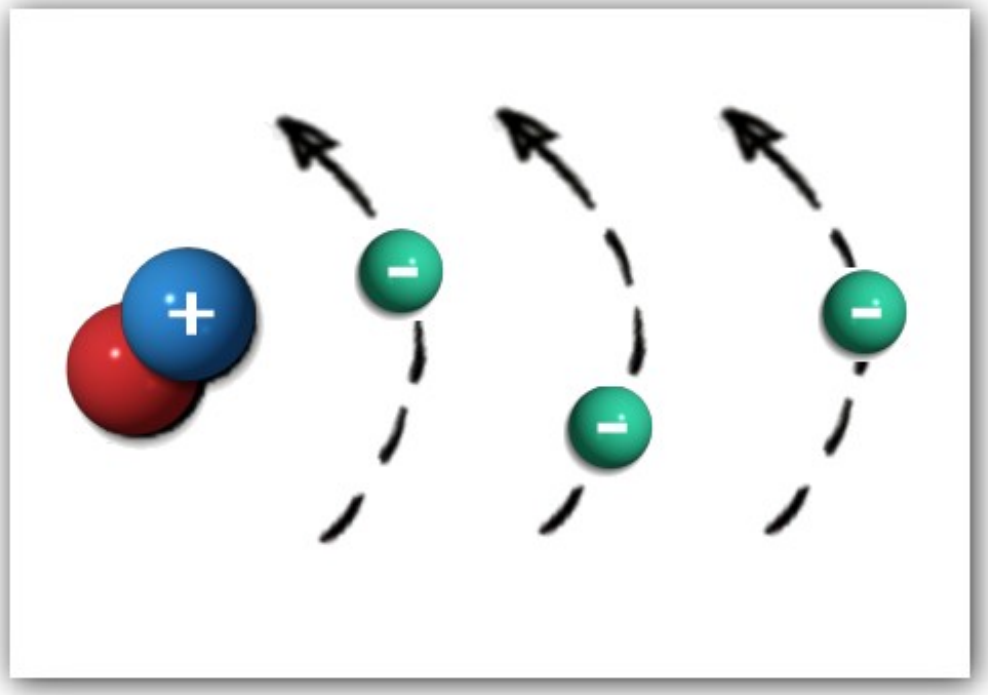
- **Diffracted or scattered from an ordered crystal**
  (X-Ray Diffraction – used to study crystal structure)



http://commons.wikimedia.org/wiki/File:X-ray_diffraction_pattern_3clpro.jpg

- **Cause the generation of X-rays of different "colors"**
  (X-Ray Fluorescence – used to determine elemental composition)

ATOMIC STRUCTURE

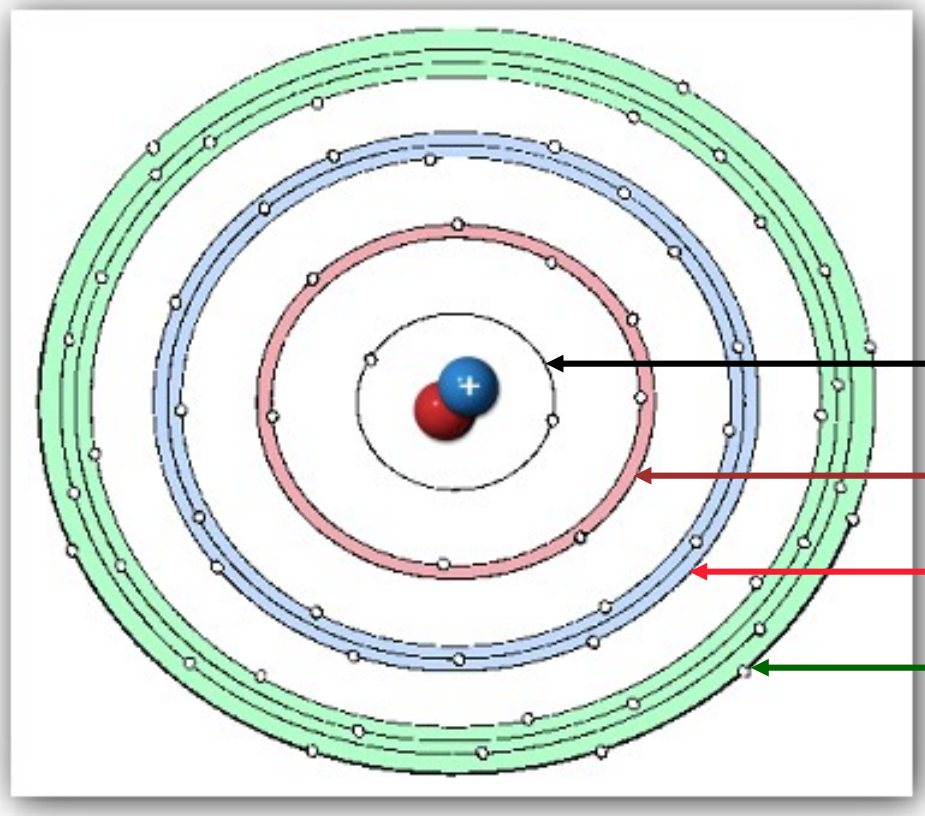


- An atom consists of a nucleus (protons and neutrons) and electrons
- Z is used to represent the atomic number of an element (the number of protons and electrons)
- Electrons spin in *shells* at specific distances from the nucleus
- Electrons take on *discrete* (quantized) energy levels (cannot occupy levels between shells
- Inner shell electrons are bound more tightly and are harder to remove from the atom

Adapted from Thermo Scientific Quant'X EDXRF training manual

ELECTRON SHELLS

Shells have specific names (i.e., K, L, M) and only hold a certain number of electrons



The shells are labelled from the nucleus outward

K shell - 2 electrons

L shell - 8 electrons

M shell - 18 electrons

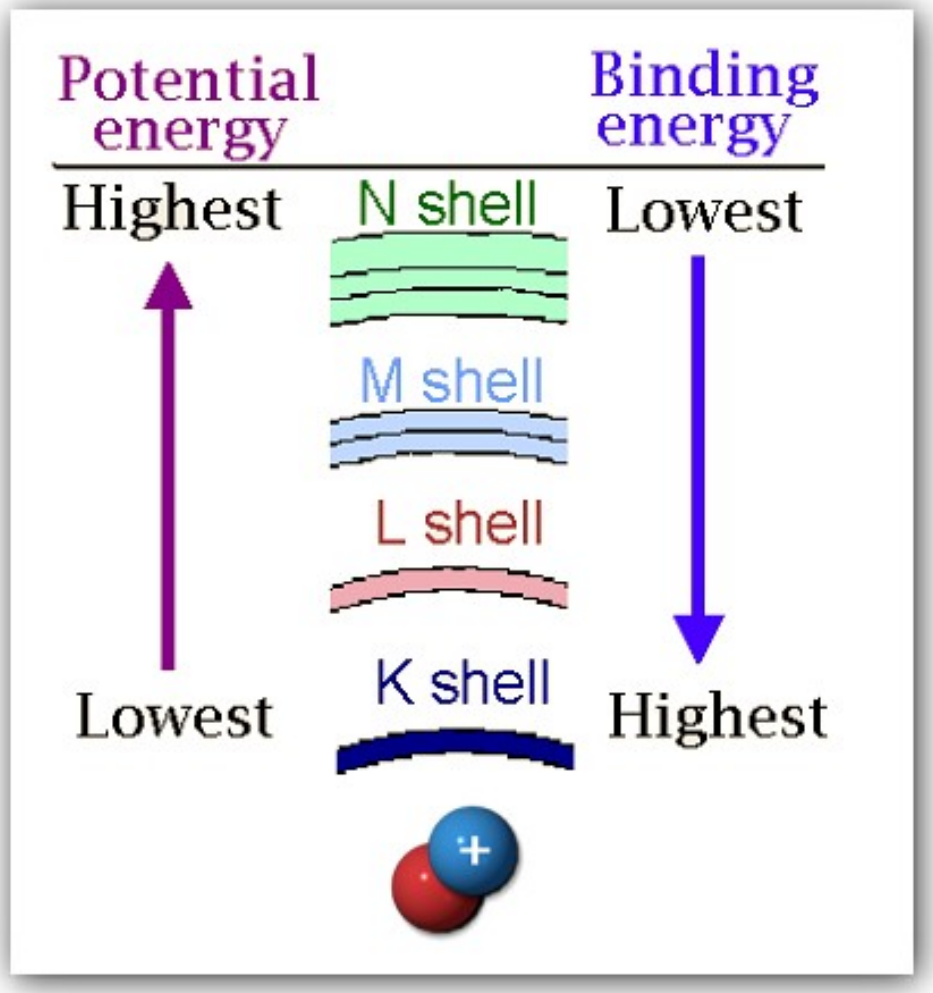
N shell - 32 electrons

X-rays typically affect only inner shell (K, L) electrons

Adapted from Thermo Scientific Quant'X EDXRF training manual

MOVING ELECTRONS TO/FROM SHELLS

Binding Energy versus Potential Energy



- **The K shell has the highest binding energy and hence it takes more energy to remove an electron from a K shell (i.e., high energy X-ray) compared to an L shell (i.e., lower energy X-ray)**

- **The N shell has the highest potential energy and hence an electron falling from the N shell to the K shell would release more energy (i.e., higher energy X-ray) compared to an L shell (i.e., lower energy X-ray)**

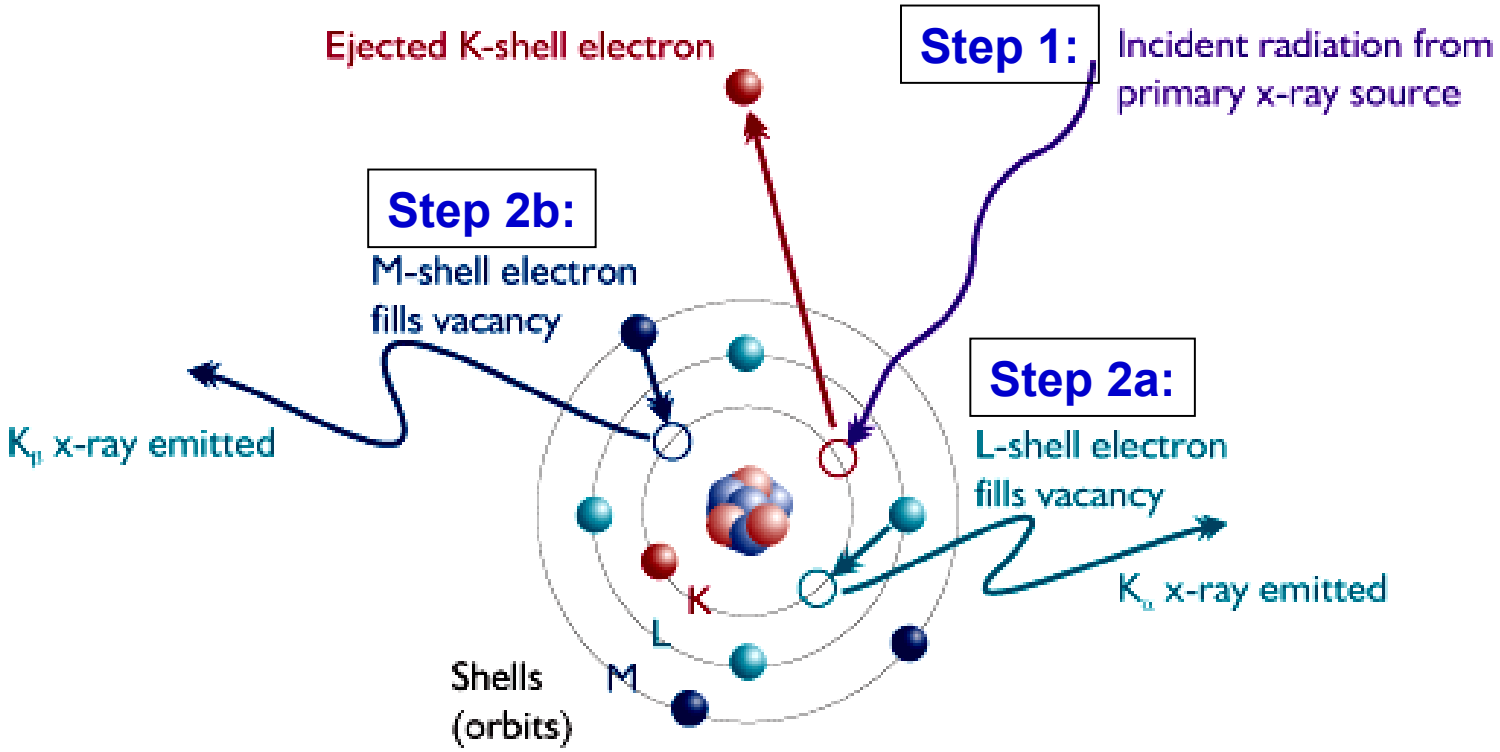
Adapted from Thermo Scientific Quant'X EDXRF training manual

XRF – A PHYSICAL DESCRIPTION

Step 1: When an X-ray photon of sufficient energy strikes an atom, it dislodges an electron from one of its inner shells (K in this case)

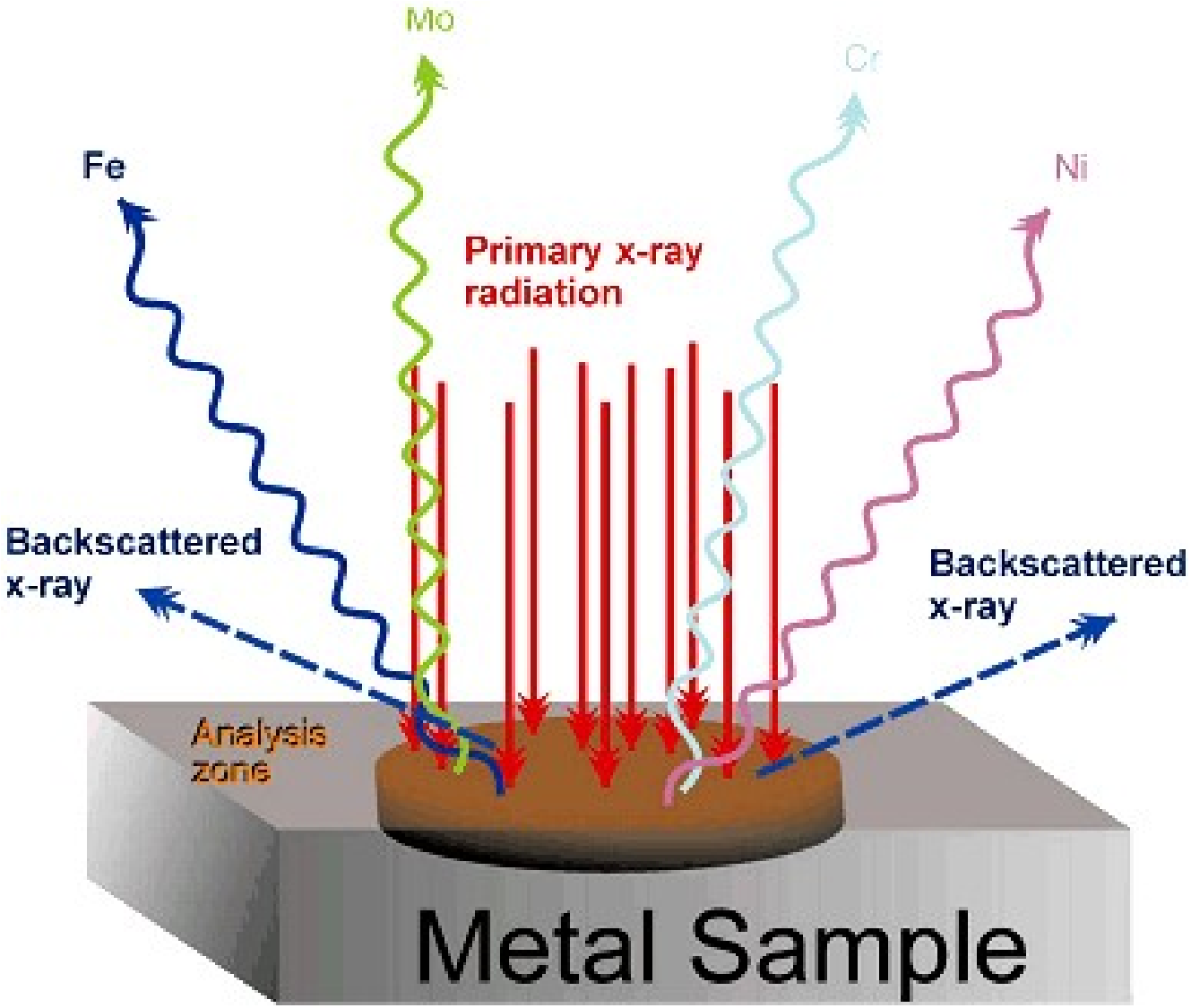
Step 2a: The atom fills the vacant K shell with an electron from the L shell; as the electron drops to the lower energy state, excess energy is released as a K_α X-ray

Step 2b: The atom fills the vacant K shell with an electron from the M shell; as the electron drops to the lower energy state, excess energy is released as a K_β X-ray



http://www.niton.com/images/XRF-Excitation-Model.gif

XRF – SAMPLE ANALYSIS

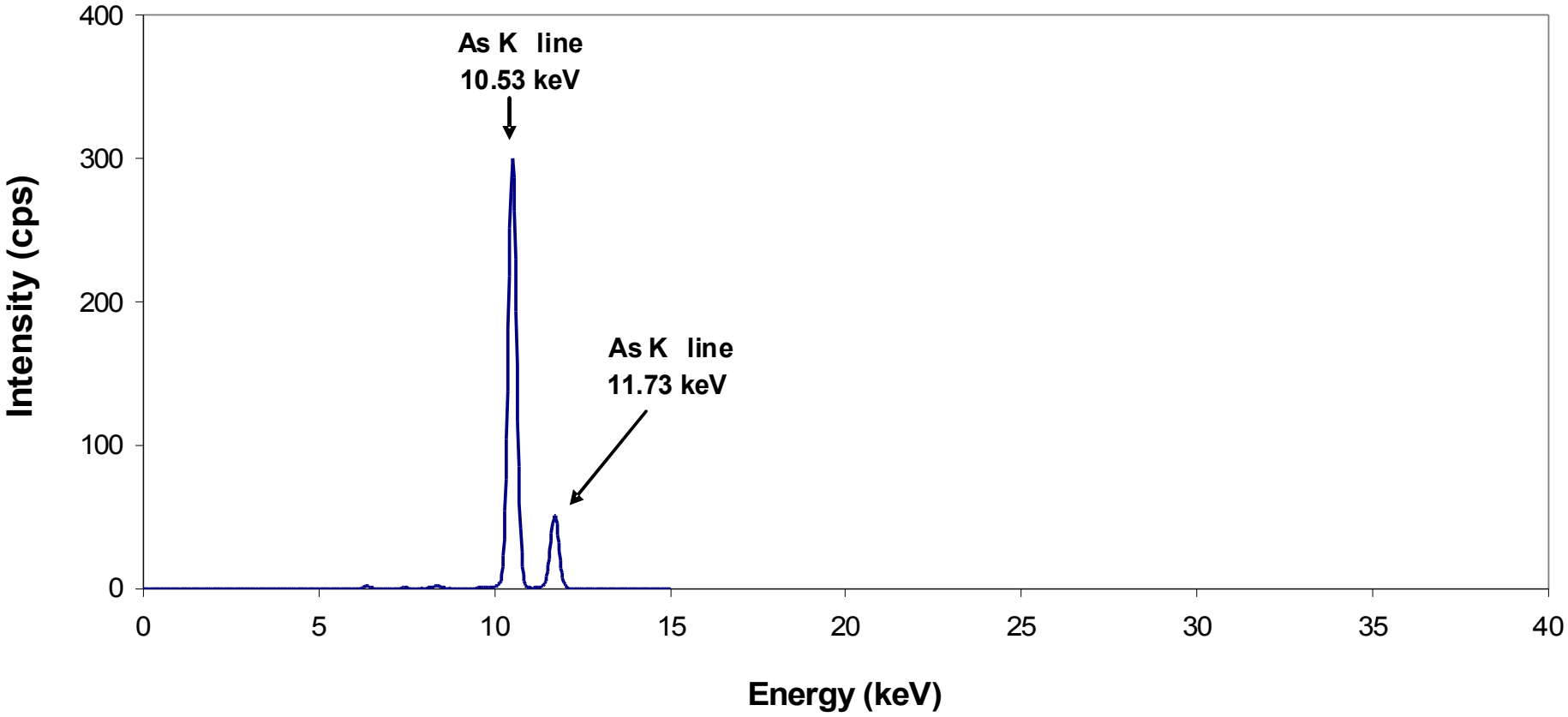


http://www.niton.com/images/fluorescence-metal-sample.gif

- **Since the *electronic energy levels for each element are different*, the energy of X-ray fluorescence peak can be correlated to a specific element**

SIMPLE XRF SPECTRUM

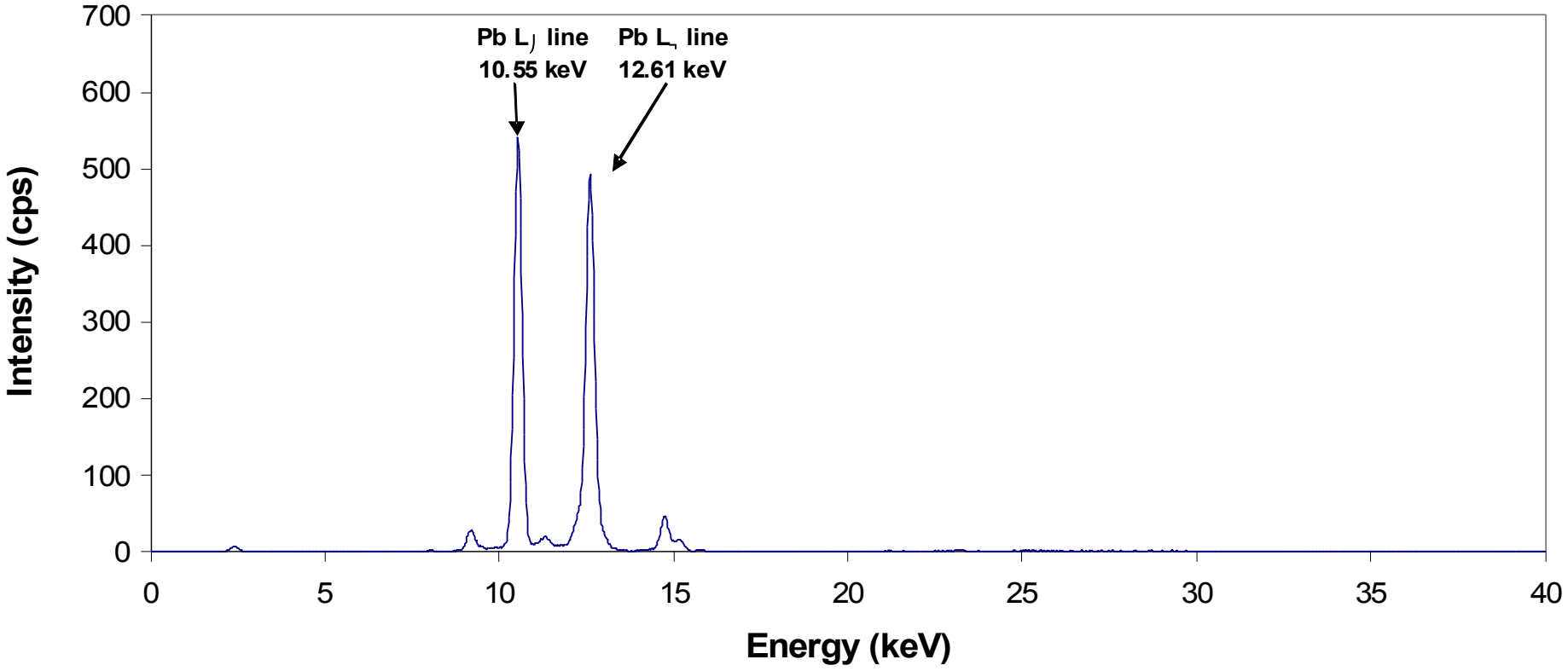
~10% As in Chinese supplement



- The presence of As in this sample is confirmed through observation of two peaks centered at energies very close (within ±0.05 keV) to their tabulated (reference) line energies
- These same two peaks will appear in XRF spectra of different arsenic-based materials (i.e., arsenic trioxide, arsenobetaine, etc.)

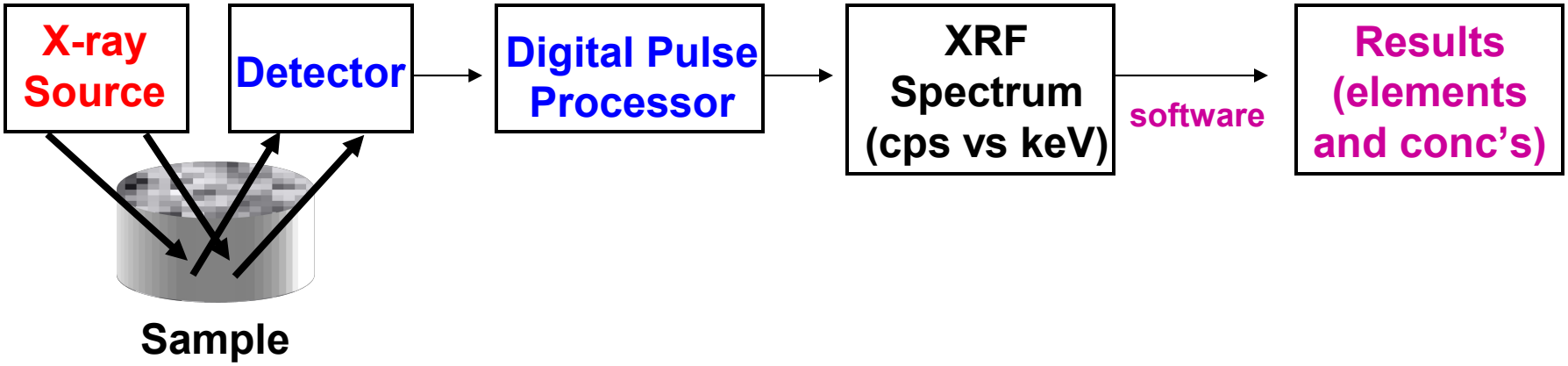
SIMPLE XRF SPECTRUM

~10% Pb in imported Mexican tableware



- The presence of Pb in this sample is confirmed through observation of two peaks centered at energies very close (within ±0.05 keV) to their tabulated (reference) line energies
- These same two peaks will appear in XRF spectra of different lead-based materials (i.e., lead arsenate, tetraethyl lead, etc.)

BOX DIAGRAM OF XRF INSTRUMENT



- **X-ray tube source**
  High energy electrons fired at anode (usually made from Ag or Rh)
  Can vary excitation energy from 15-50 kV and current from 10-200 μA
  Can use filters to tailor source profile for lower detection limits

- **Silicon Drift Detector (SDD) and digital pulse processor**
  Energy-dispersive m*ulti-channel analyzer* – no monochromator needed, Peltier-cooled solid state detector monitors both the energy and number of photons over a preset measurement time
  The energy of photon in keV is related to the *type* of element
  The emission rate (cps) is related to the *concentration* of that element

- **Analyzer software converts spectral data to direct readout of results**
  Concentration of an element determined from factory calibration data, sample thickness as estimated from source backscatter, and other parameters

DIFFERENT TYPES OF XRF INSTRUMENTS

Handheld

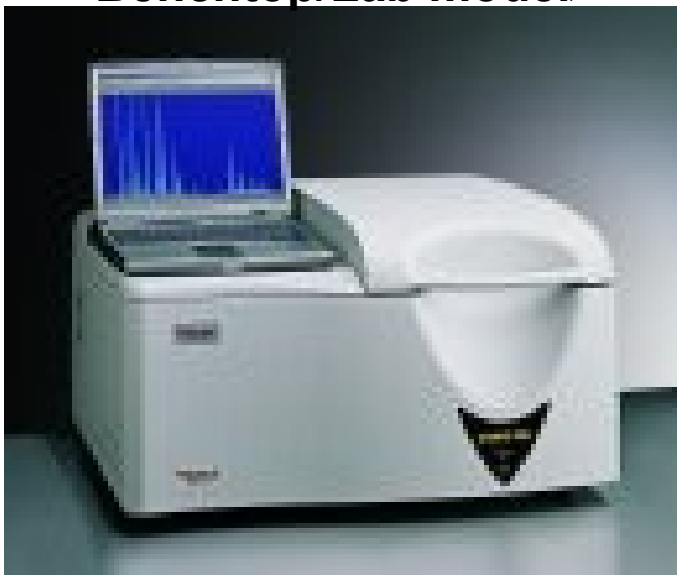
Bruker Tracer V
http://www.brukeraxs.com/

- **EASY TO USE** (“point and shoot”)
- Used for **SCREENING**
- Can give **ACCURATE RESULTS** when used by a knowledgeable operator
- ***Primary focus of these materials***

Portable

Innov-X X-50
http://www.innovx.com/

Benchtop/Lab model



Thermo/ARL Quant’X
http://www.thermo.com/

- **COMPLEX SOFTWARE**
- Used in **LAB ANALYSIS**
- Designed to give **ACCURATE RESULTS** (autosampler, optimized excitation, report generation)

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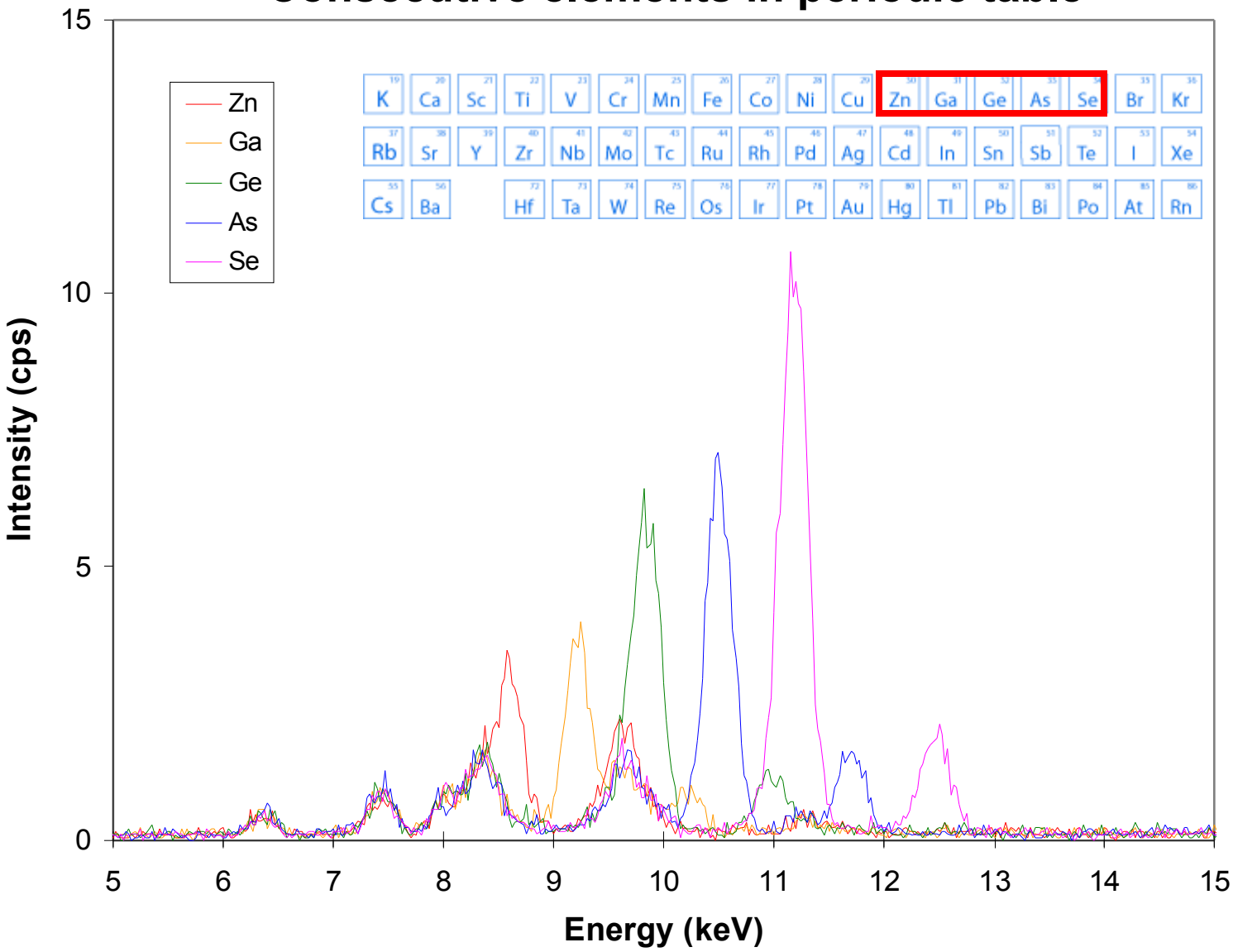
XRF SPECTRA

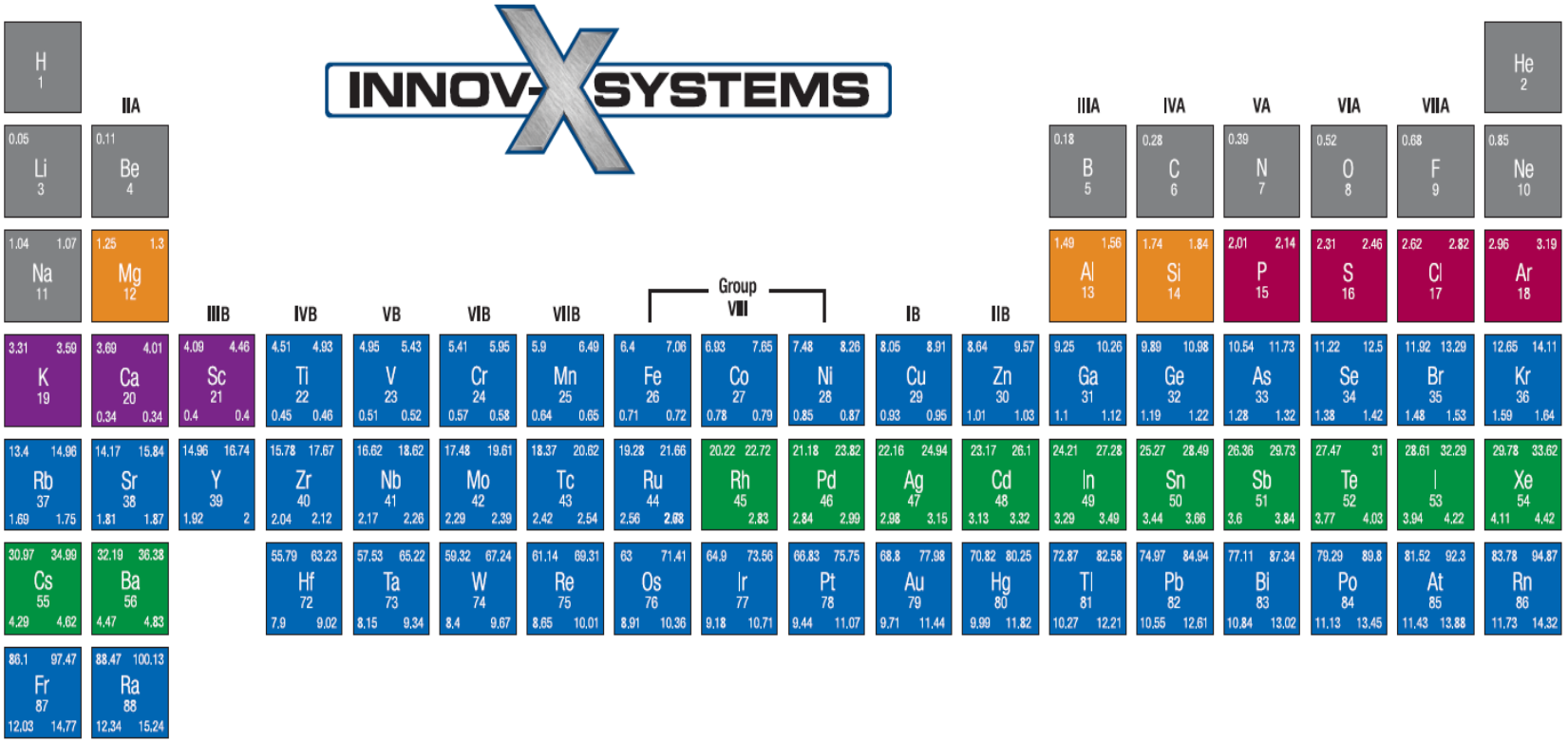
Consecutive elements in periodic table



- **Plotting only a portion of the XRF spectra of several different elements**
- **Note periodicity - energy is proportional to Z^2 (Moseley's law)**

PERIODIC TABLE OF XRF FLUORESCENCE DATA

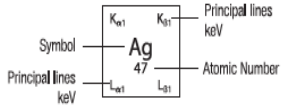
Including K and L line energies & detection limits



Alloy Elements and Detection Limit Guidelines:

Elements Detected Magnesium (Mg, Z=12) through Silicon (Si, Z=14) and Titanium (Ti, Z=22) through Plutonium (Pu, Z=94) typically 0.1% - some elements as low as 0.01%

Low-Density Sample Types (Soils, powders, liquids)



Requires vacuum, LOD 0.2 – 3%

250 - 2,500 ppm

50 - 150 ppm

LOD 1% - 5%

10 - 100 ppm

Not Measured

Detection limits are a function of testing time, sample matrix and presence of interfering elements. Detection limits are estimates based on 1-2 minutes test times and detection confidence of 3σ (99.7% confidence). Interference-free detection limits are intended as guidelines: please contact Innov-X Systems to discuss your specific application.

Adapted from Innov-X handout for handheld XRF analyzers
Note similar reference tables available from other XRF vendors

XRF ENERGIES FOR VARIOUS ELEMENTS

Generalizations based on use of field portable analyzers

- **ORGANIC ELEMENTS (i.e., H, C, N, O) DO NOT GIVE XRF PEAKS**
  Fluorescence photons from these elements are too low in energy to be transmitted through air and are not efficiently detected using conventional Si-based detectors

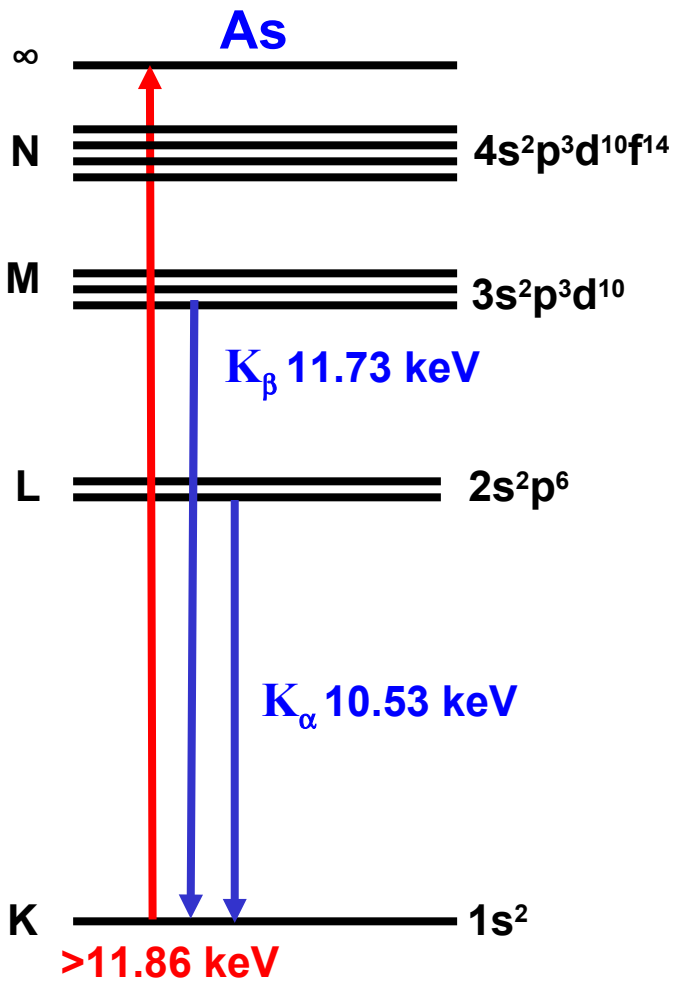
- **LOW Z ELEMENTS (i.e., Cl, Ar, K, Ca) GIVE ONLY K PEAKS**
  L peaks from these elements are too low in energy (these photons are not transmitted through air and not detected with conventional Si-based detectors)

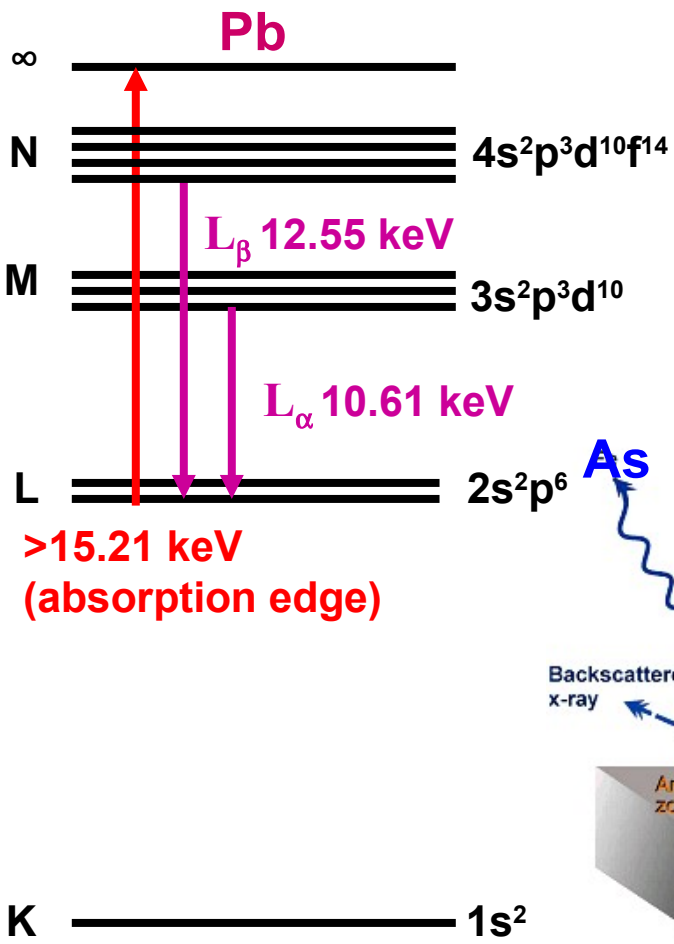
- **HIGH Z ELEMENTS (i.e., Ba, Hg, Pb, U) GIVE ONLY L LINES**
  K peaks from these elements are too high in energy (these electrons have high binding energies and cannot be removed with the limited voltage available in field portable analyzers)

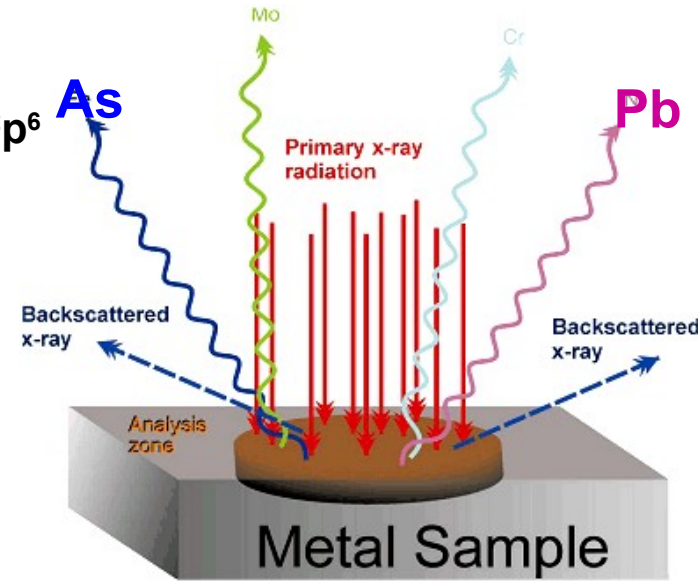
- **MIDDLE Z ELEMENTS (i.e., Rh through I) MAY GIVE BOTH K AND L LINES**

XRF – MORE DETAILED DESCRIPTION

Note energy level diagrams are not drawn to scale





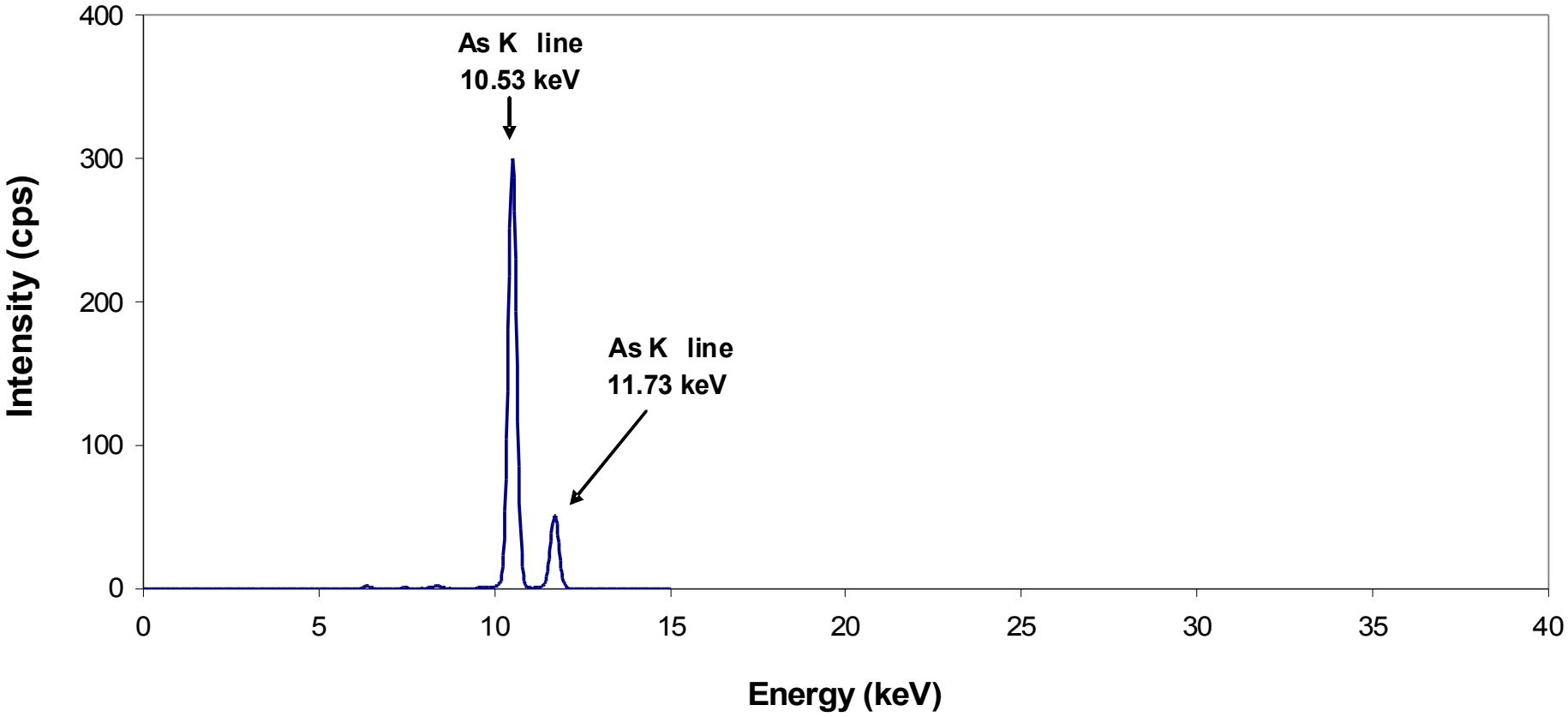


http://www.niton.com/images/fluorescence-metal-sample.gif

- Since *XRF affects inner shell and not bonding electrons*, the XRF spectrum of an element is *independent* of its chemical form (i.e., spectra of lead, lead arsenate, and tetraethyl lead will ALL show peaks at 10.61 and 12.55 keV)

K LINE SERIES

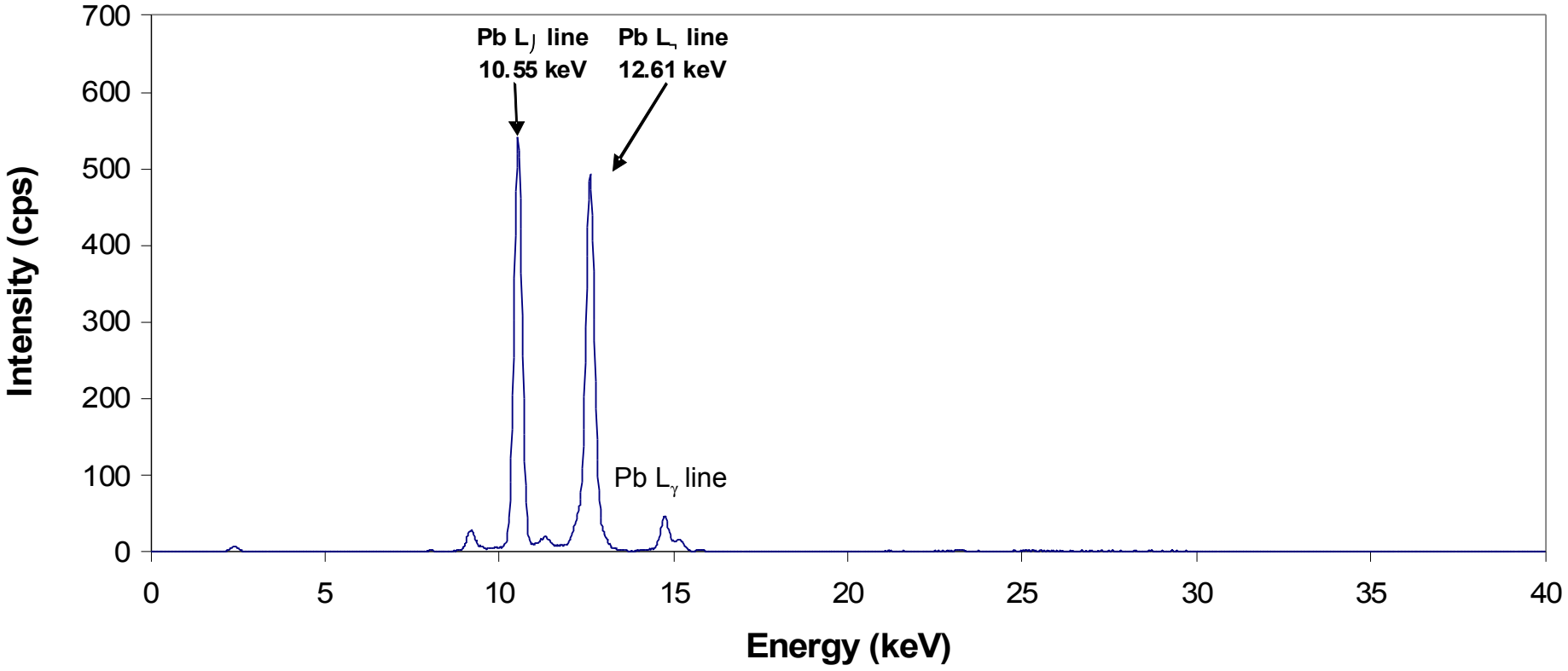
~10% As in Chinese supplement



- L lines not observed (1.28 and 1.32 keV - too low in energy to be excited)
- K_α and K_β peak energies are often close together (1.2 keV apart for As)
- K lines observed for low to medium Z elements (i.e., Cl, Fe, As)
- K_α and K_β peaks have typical ratio of ~ 5 to 1

L LINE SERIES

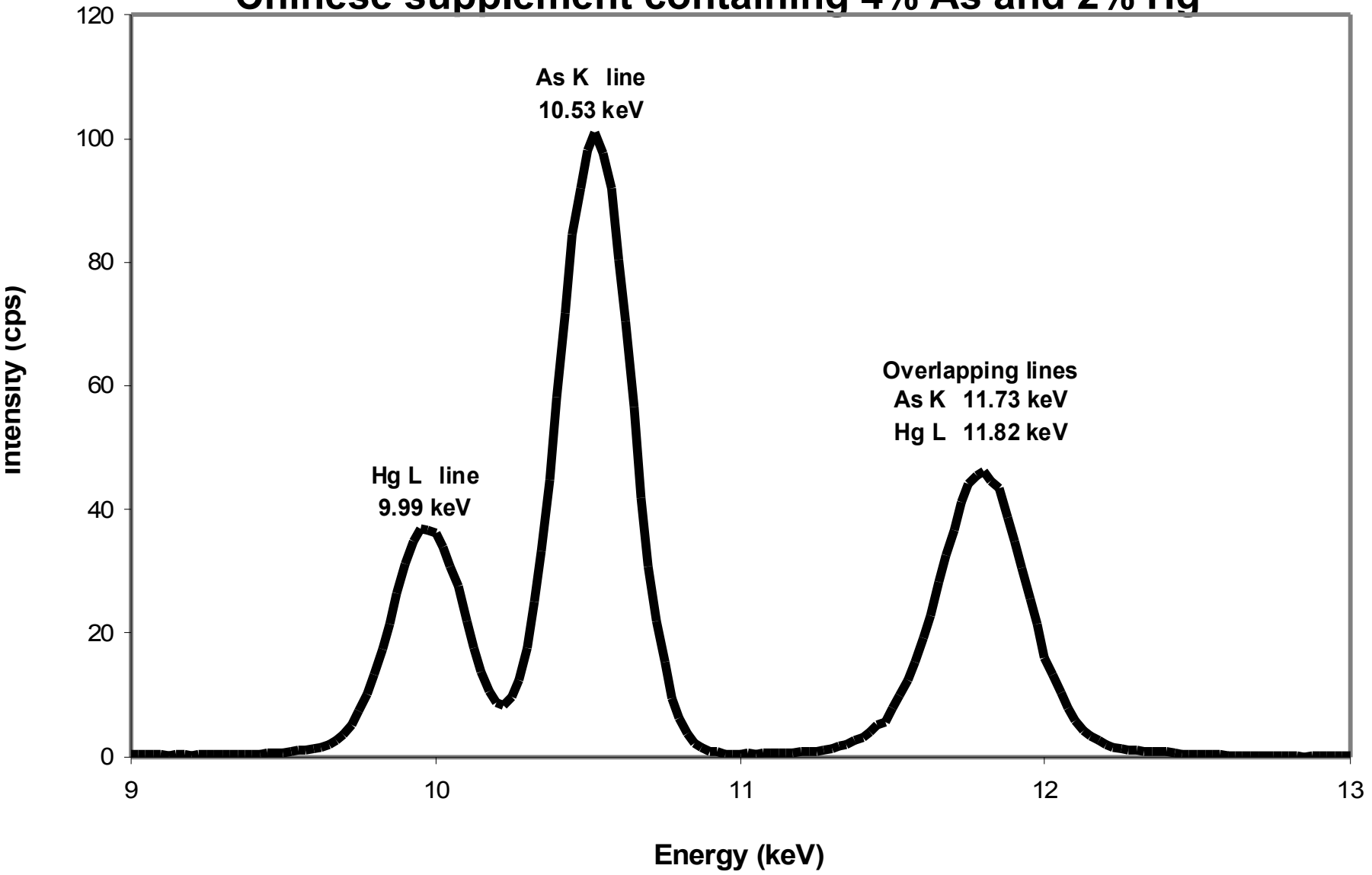
~10% Pb in imported Mexican tableware



- K lines not observed (75.0 and 94.9 keV - too high in energy to be excited)
- L_α and L_β peak energies are often further apart (2.1 keV apart for Pb)
- L lines observed for high Z elements (i.e., Hg, Pb, Th)
- L_α and L_β peaks have typical ratio of ~ 1 to 1

MORE COMPLEX XRF SPECTRUM

Chinese supplement containing 4% As and 2% Hg

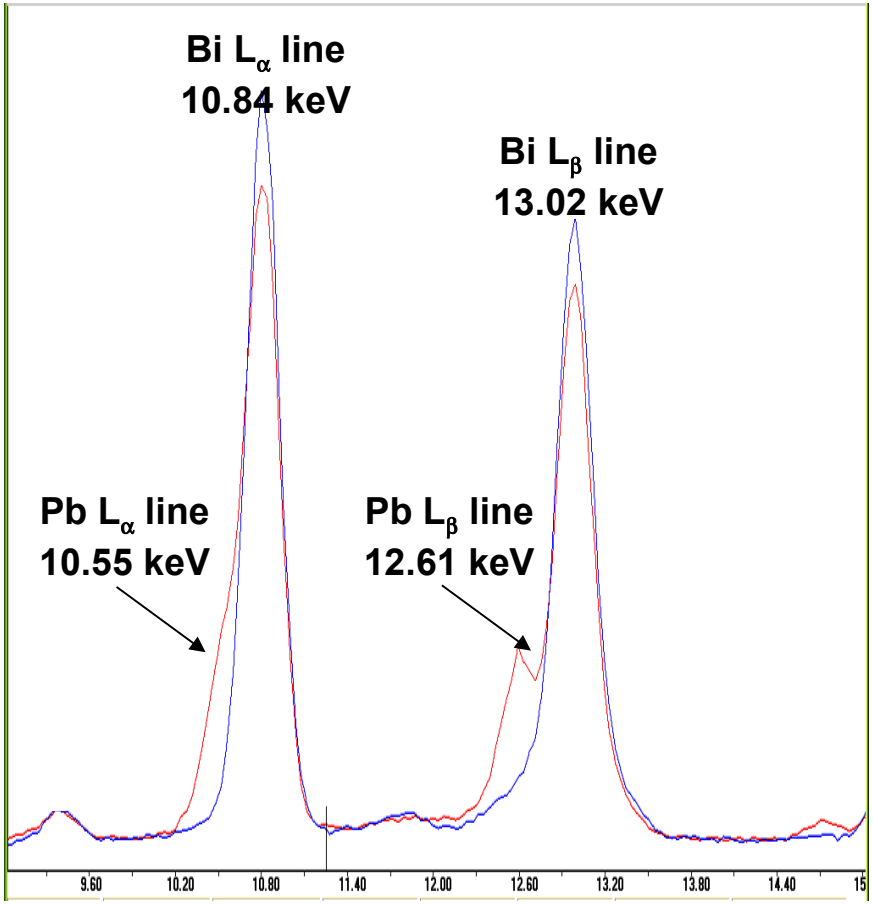


- **Line overlaps are possible and <u>users must evaluate spectrum</u> to confirm the presence or absence of an element**

EFFECT OF DETECTOR RESOLUTION

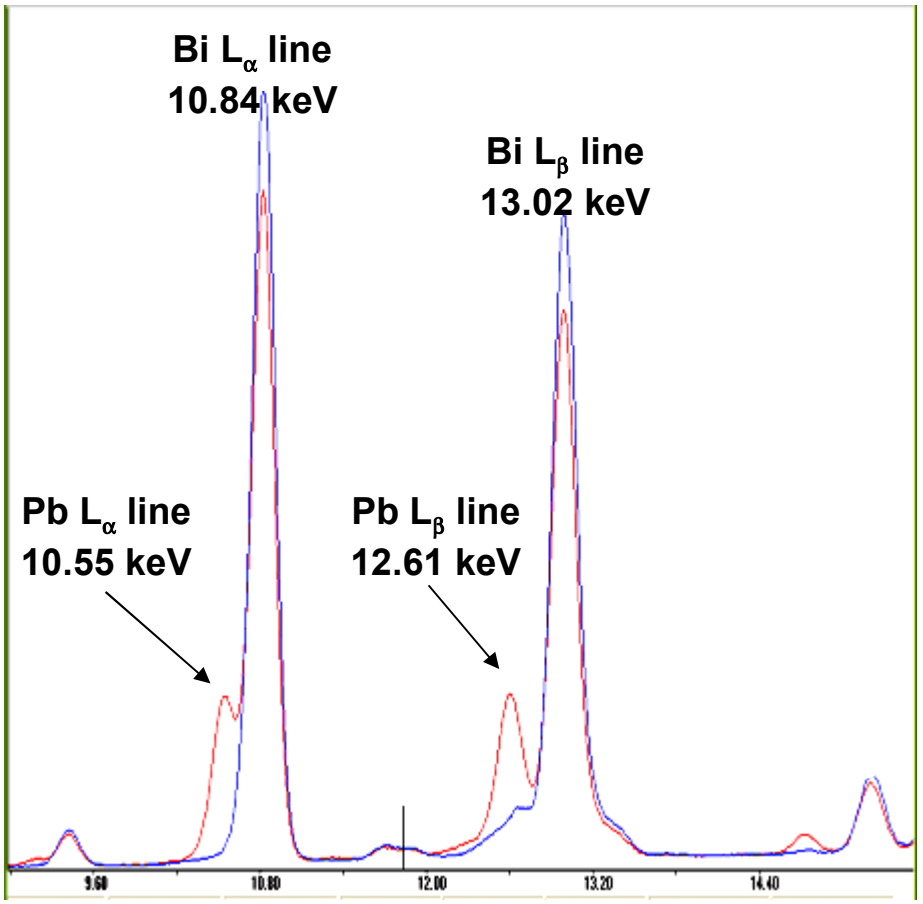
Spectra of 900 ppm Pb added into Pepto-Bismol

Older Si(PIN) detector



- Resolution ~0.2 keV (FWHM)
- Cannot resolve Pb and Bi peaks

Newer SDD



- Resolution ~0.15 keV (FWHM)
- Can resolve Pb and Bi peaks

Adapted from Bruce Kaiser, Bruker AXS

ARTIFACT PEAKS

Arising from X-ray tube source

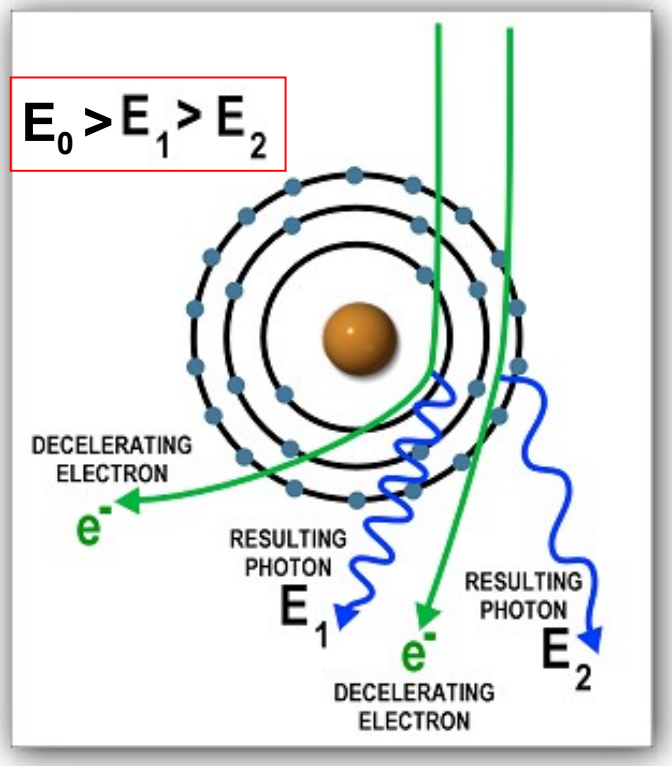
- **Electrons with high kinetic energy (typically 10-50 kV) strike atoms in the X-ray tube source target (typically Rh or Ag) and transfer energy**

- **The interaction of X-ray source photons with the sample generates several characteristic features in an XRF spectrum which may include the following:**

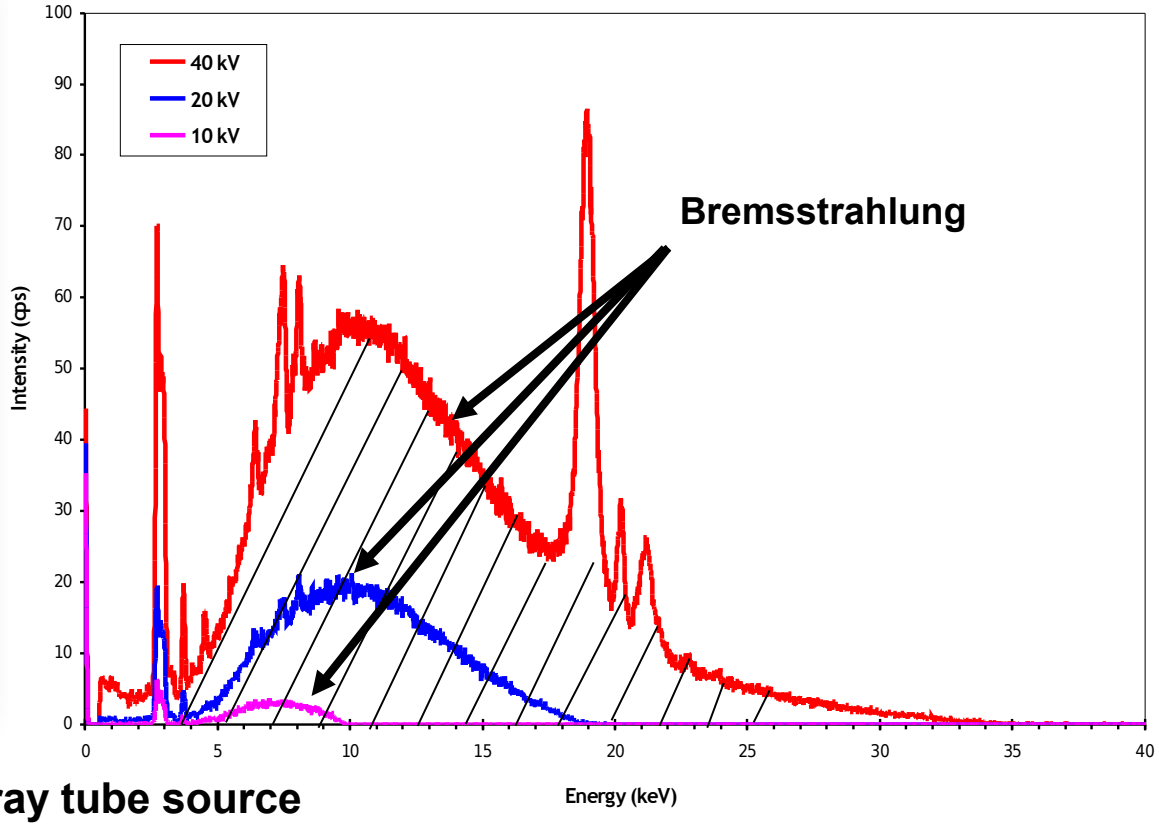
  - **Bremsstrahlung**
  - **Rayleigh peaks**
  - **Compton peaks**

BREMSSTRAHLUNG

Continuum/backscatter from cellulose sample



Adapted from Thermo Scientific Quant'X EDXRF training manual



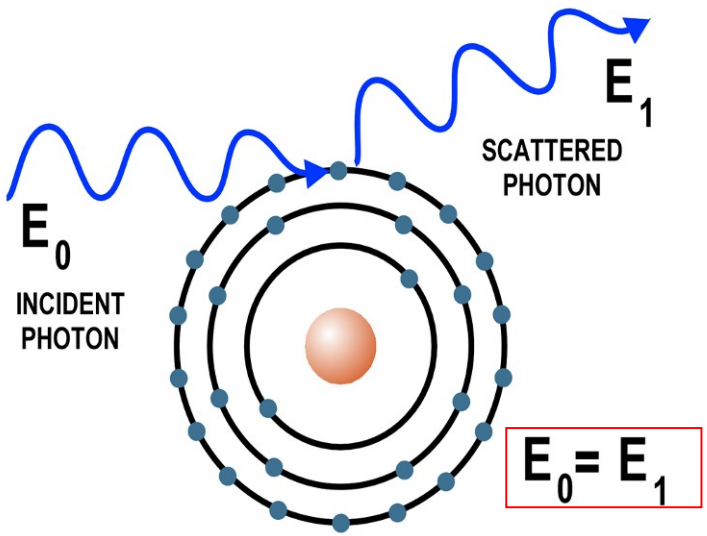
E_0 = initial energy of electron in X-ray tube source

E_1 , E_2 = energy of X-ray

- Very broad peak due to backscattering of X-rays from sample to detector that may appear in all XRF spectra
- Maximum energy of this peak limited by kV applied to X-Ray tube, maximum intensity of this peak is ~ 2/3 of the applied keV
- More prominent in XRF spectra of less dense samples which scatter more of X-ray source photons back to the detector

RAYLEIGH PEAKS

Elastic scattering from metal alloy sample



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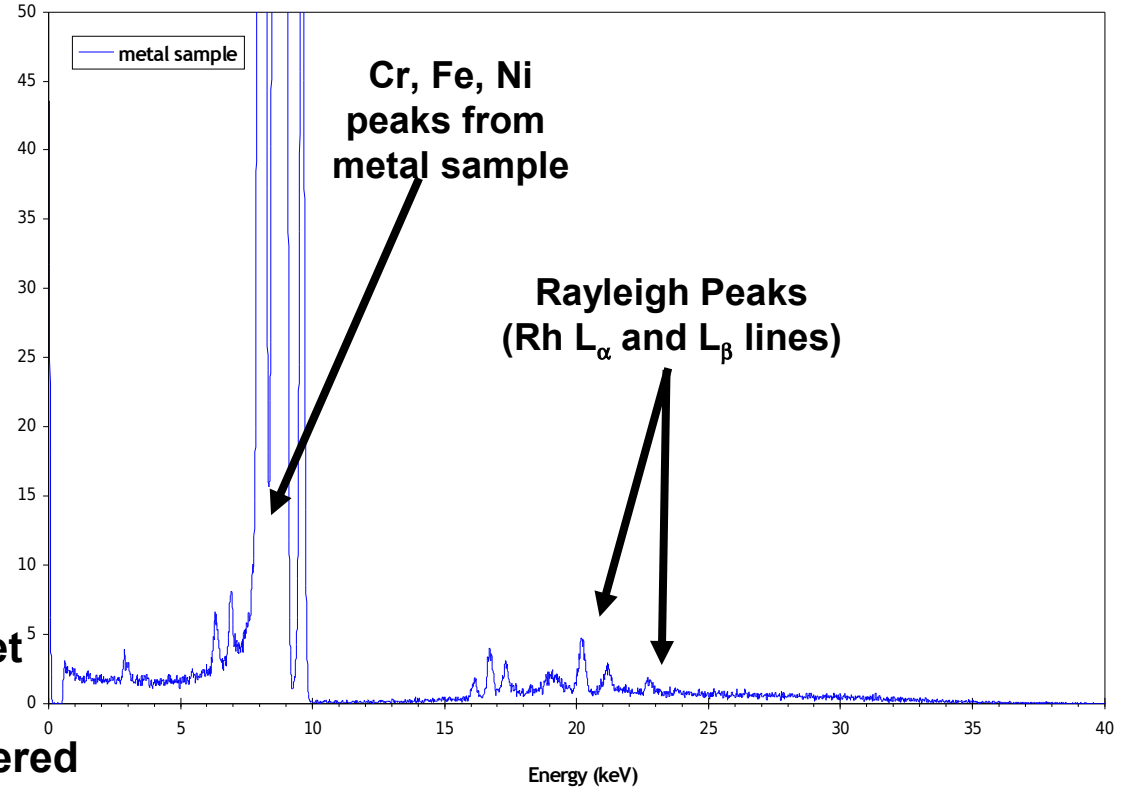


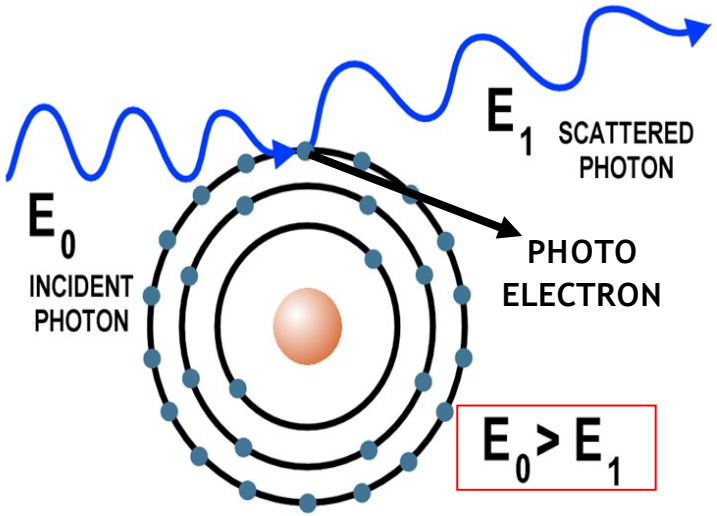
E_0 = initial energy of X-ray from target element in x-ray tube source

E_1 = energy of X-ray elastically scattered from (typically dense) sample

- Peaks arising from target anode in X-ray tube source (Rh in this case) that may appear in all XRF spectra acquired on that instrument
- No energy is lost in this process so peaks show up at characteristic X-ray energies (Rh L_α and L_β at 20.22 and 22.72 keV in this case)
- Typically observed in spectra of dense samples as weak peaks (due to increased absorption of X-ray source photons by sample)

COMPTON PEAKS

Inelastic scattering from cellulose sample



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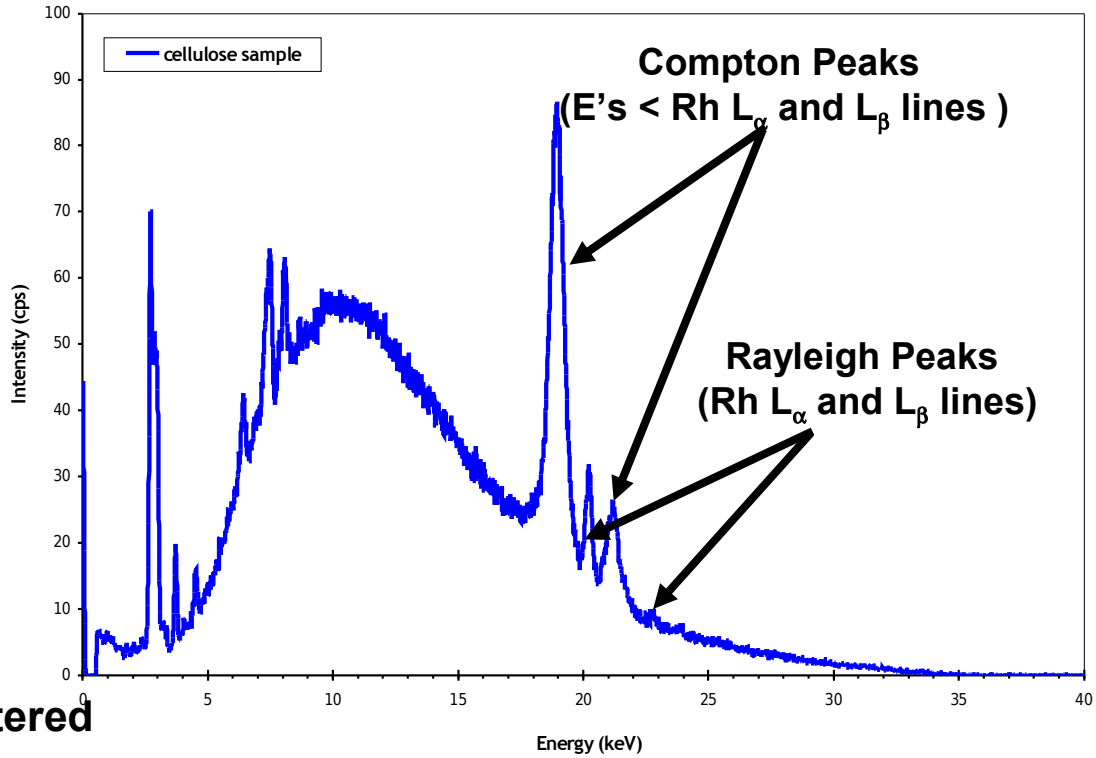


E_0 = initial energy of X-ray from target element in x-ray tube source

E_1 = energy of X-ray inelastically scattered from (typically non-dense) sample

- Peaks arising from target element in X ray tube (again, Rh in this case) that may appear in all XRF spectra acquired on that instrument
- Some energy is lost in this process so peaks show up at energies slightly less than characteristic X-ray tube target energies
- Typically observed in spectra of low density samples as fairly intense peaks (note these peaks are wider than Rayleigh peaks)

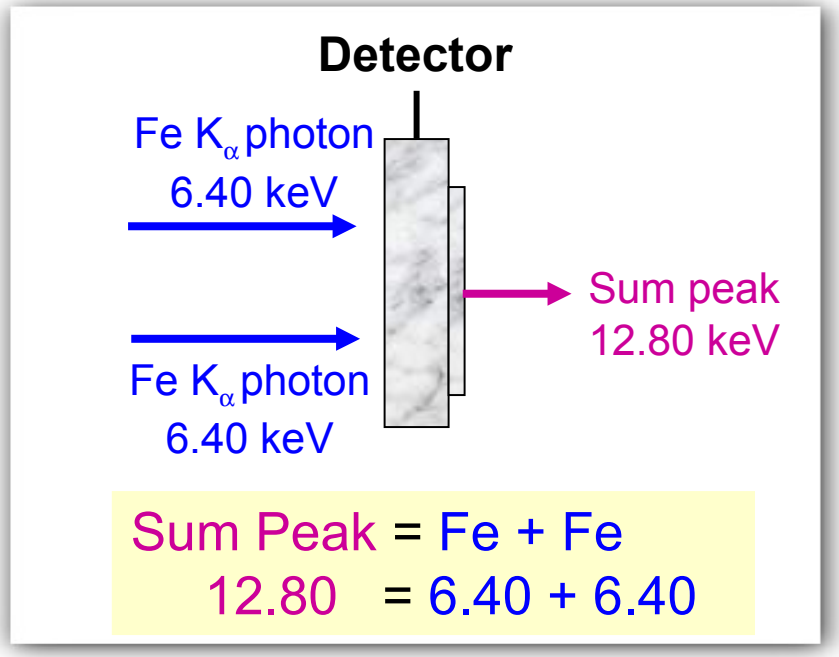
ARTIFACT PEAKS

Arising from detection process

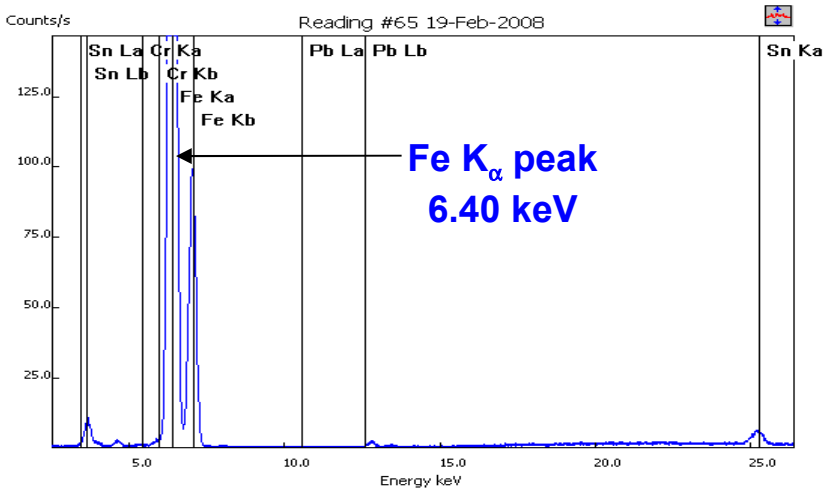
- **The interaction of X-ray fluorescence photons from the sample with the detector can generate several different types of artifact peaks in an XRF spectrum which may include the following:**
  - **Sum peaks**
  - **Escape peaks**

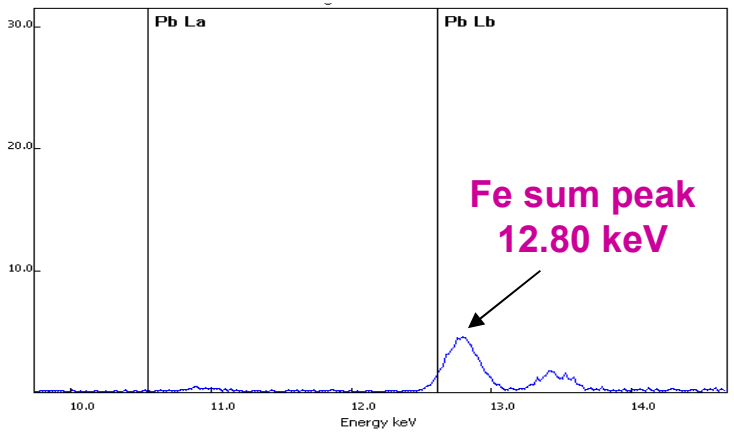
SUM PEAKS

Example from analysis of Fe sample



Adapted from Thermo Scientific Quant'X EDXRF training manual

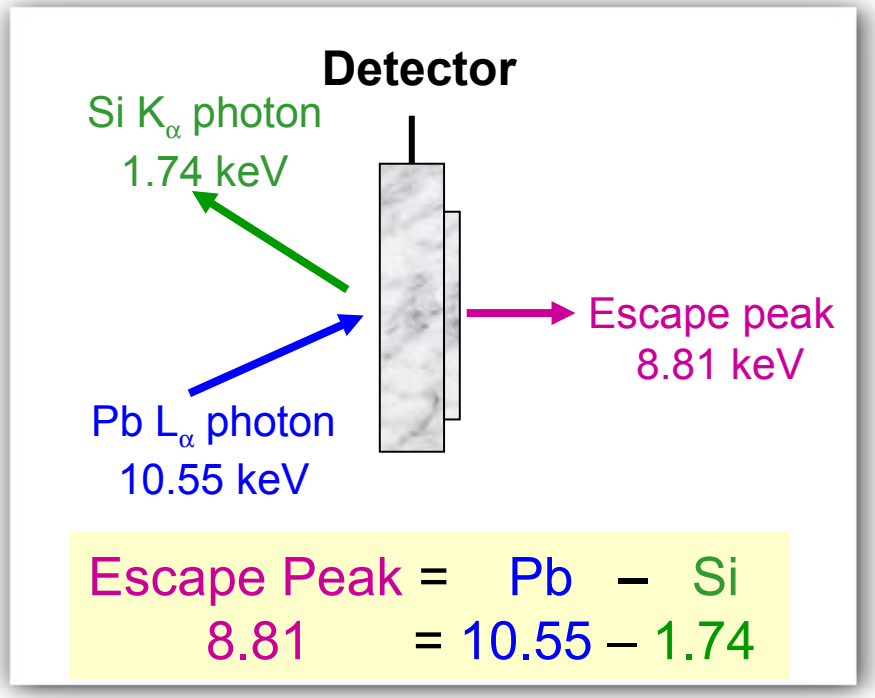




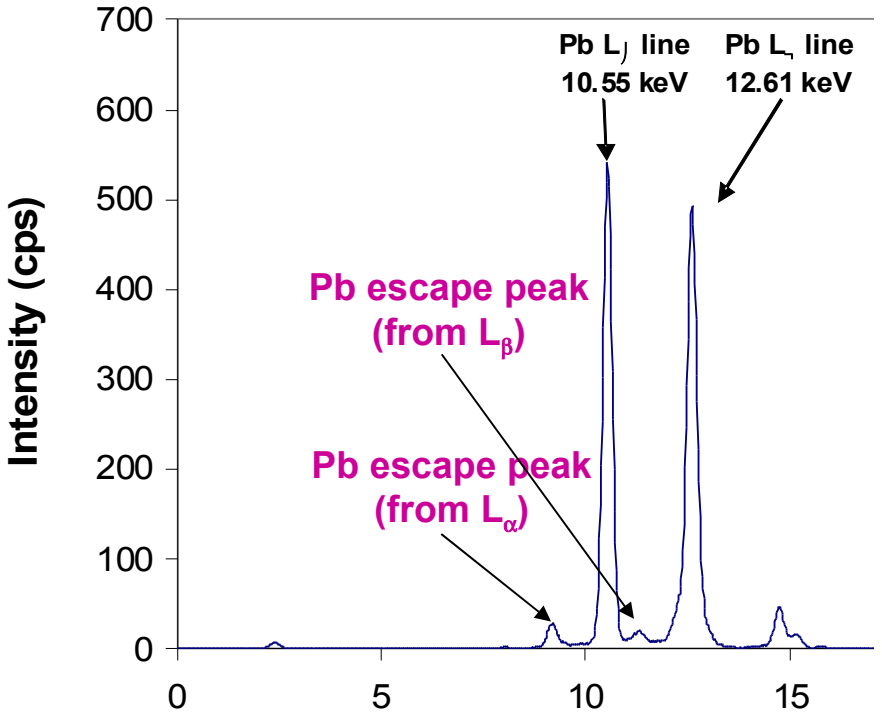
- **Artifact peak due to the arrival of 2 photons at the detector at exactly the same time (i.e., $K_\alpha + K_\alpha$, $K_\alpha + K_\beta$)**
- **More prominent in XRF spectra that have high concentrations of an element**
- **Can be reduced by keeping count rates low**

ESCAPE PEAKS

Example from analysis of Pb sample

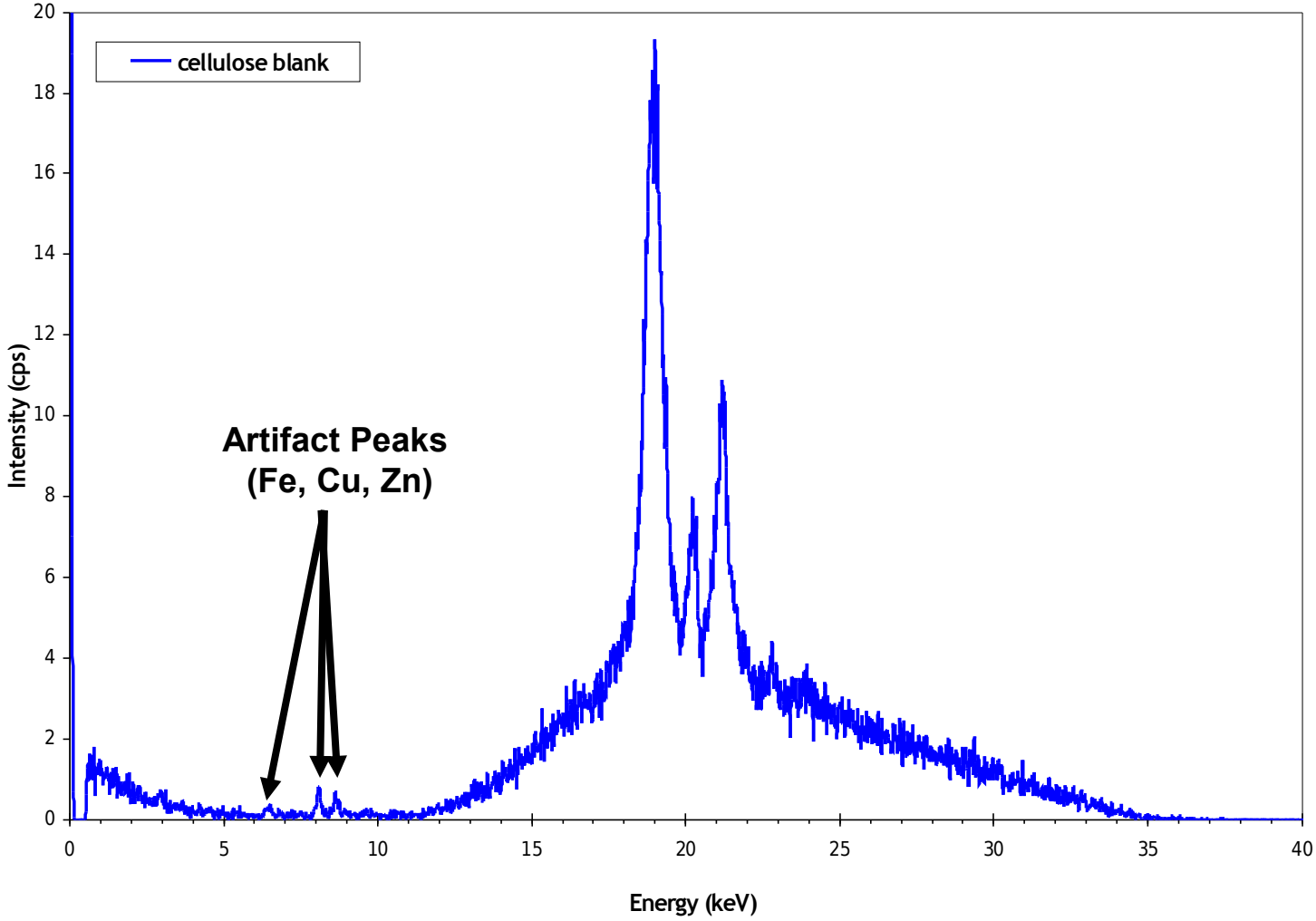


Adapted from Thermo Scientific Quant'X EDXRF training manual



- **Artifact peak due to the absorption of some of the energy of a photon by Si atoms in the detector ($E_{observed} = E_{incident} - E_{Si}$ where $E_{Si} = 1.74$ keV)**
- **More prominent in XRF spectra that have high concentrations of an element and for lower Z elements**
- **Can be reduced by keeping count rates low**

ARTIFACT PEAKS DUE TO BLANK MEDIA



- May observe peaks due to contaminants in XRF cups, Mylar film, and matrix
- In this case, the cellulose matrix is highly pure and the peaks are due to trace elements in the XRF analyzer window and detector materials
- This can complicate interpretation (false positives)

SUMMARY OF FACTORS THAT COMPLICATE INTERPRETATION OF XRF SPECTRA

Elements in the sample may produce 2 or more lines

- K_{α}, K_{β}, L_{α}, L_{β}, (we use simplified nomenclature and discussed only α and β lines)
- L_{γ}, $L_{\alpha 1}$, $L_{\beta 1}$, $L_{\beta 2}$ (can also have $\alpha 1$ and $\alpha 2$ lines, $\beta 1$ and $\beta 2$ lines, γ lines, etc.)

Peak overlaps arising from the presence of multiple elements in the sample and limited detector resolution

Peaks from X-ray source

- Bremsstrahlung (more prominent in less dense samples)
- Rayleigh peaks from X-ray source target (typically Ag L_{α}, L_{β})
- Compton peaks from X-ray source target (typically at energies < Ag L_{α}, L_{β})

Sum peaks (two X-ray photons arriving at the detector at the same time)

- $E = K_{\alpha} + K_{\alpha}$
- $E = K_{\alpha} + K_{\beta}$

Escape peaks (Si in the detector absorbing some of the energy from a X-ray)

- $E = K_{\alpha} - K_{\alpha \text{ for Si}}$ (where Si line energy = 1.74 keV)
- $E = L_{\alpha} - K_{\alpha \text{ for Si}}$

Other artifact peaks

- Product packaging, XRF cup, Mylar film, (measure what you want to measure)
- Contaminants on XRF window or trace levels of elements in XRF window or detector

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   - Different types of XRF instruments

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   - XRF spectra of different elements
   - Limited resolution and overlapping peaks
   - Artifact peaks

3. **QUALITATIVE AND QUANTITATIVE ANALYSIS**
   - Confirmation of detection of an element
   - Different calibration models
   - Example calibration curves

4. **APPLICATIONS OF XRF**
   - Screening for toxic elements in large numbers of samples
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5. **CONCLUSIONS**
   - XRF advantages and limitations
   - References and additional reading

QUALITATIVE ANALYSIS

Issues to consider

Question: What is the GOAL of the analysis and WHAT ELEMENTS do we want to look for (toxic elements such as As, Cd, Hg, Pb; nutrient elements such as Ca, Fe)?

Answer: ***Define the problem (what to measure, typical concentration range, required detection limit, accuracy, precision, etc.)***

Question: Are there any potential SPECTRAL OVERLAPS with other elements in sample?

Answer: ***Compare line energies of target elements and other elements to identify any possible interferences***

Question: If we get a "positive" (detection of a toxic element), do we know for certain that it is IN THE SAMPLE and not in the product packaging or the background materials used to hold the sample?

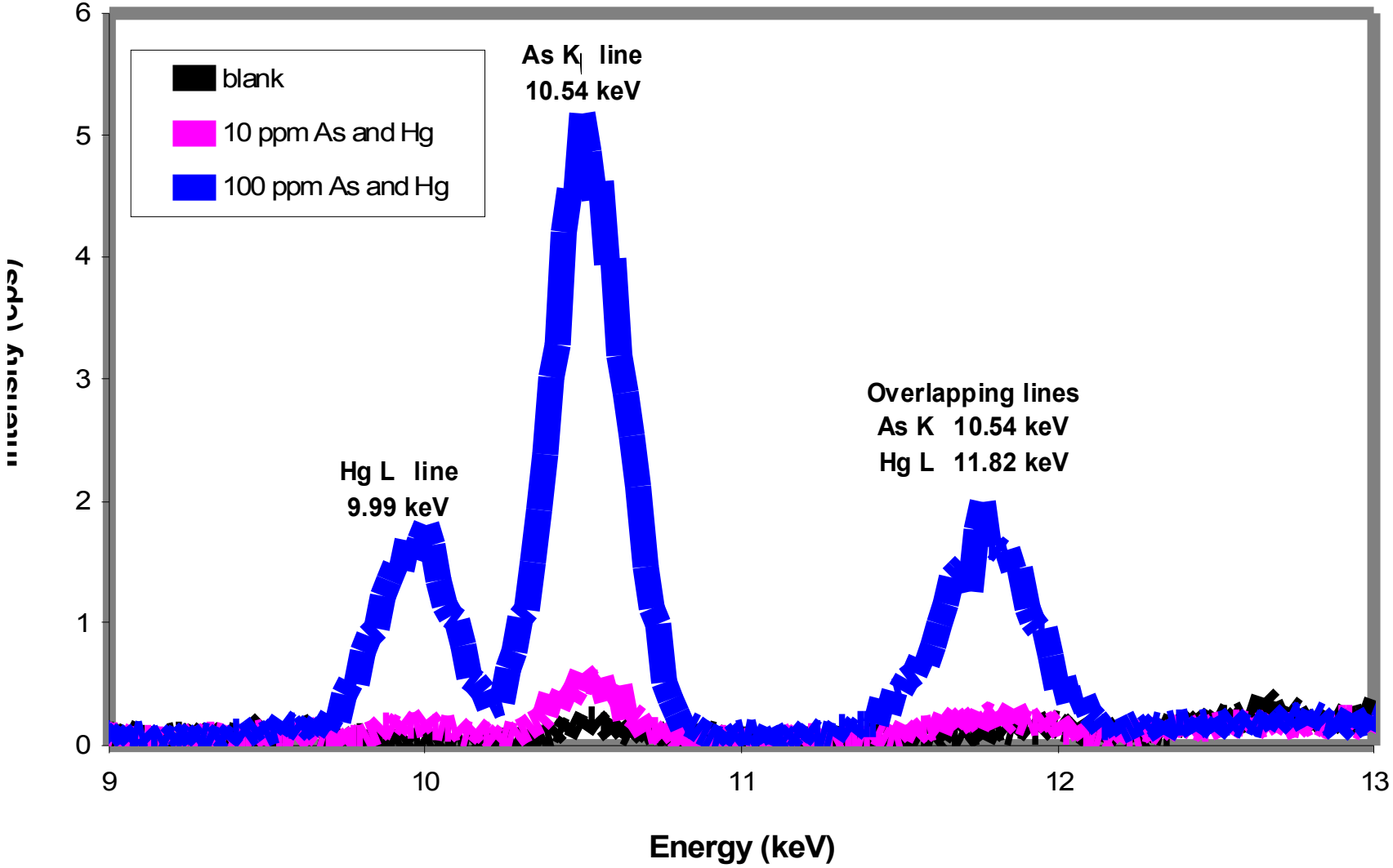
Answer: ***Measure what you want to measure and be sure to do "blanks"***

Question: How do we know that the analyzer software is not giving ERRONEOUS RESULTS (false positives or false negatives)?

Answer: ***Users must evaluate the spectrum to verify the reported results – positive identification of an element requires observation of two peaks at energies close to their tabulated values***

QUALITATIVE ANALYSIS

Spectra for positive, tentative, and negative identifications

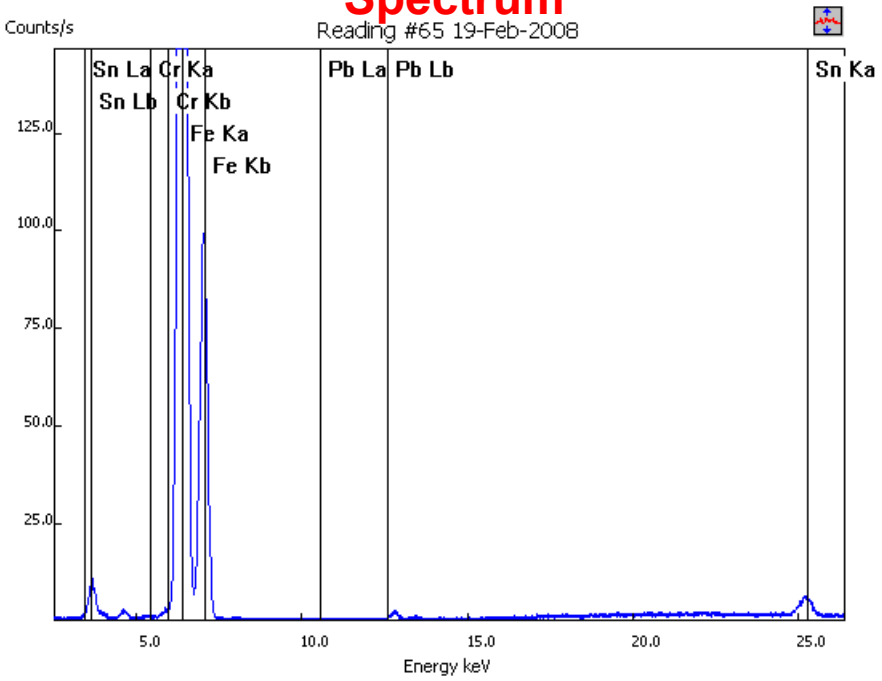


- As and Hg clearly present in blue spectrum (see both α and β peaks)
- As and Hg possibly present in purple spectrum (β peaks barely > blank)
- As and Hg not present in black spectrum (no visible peaks)

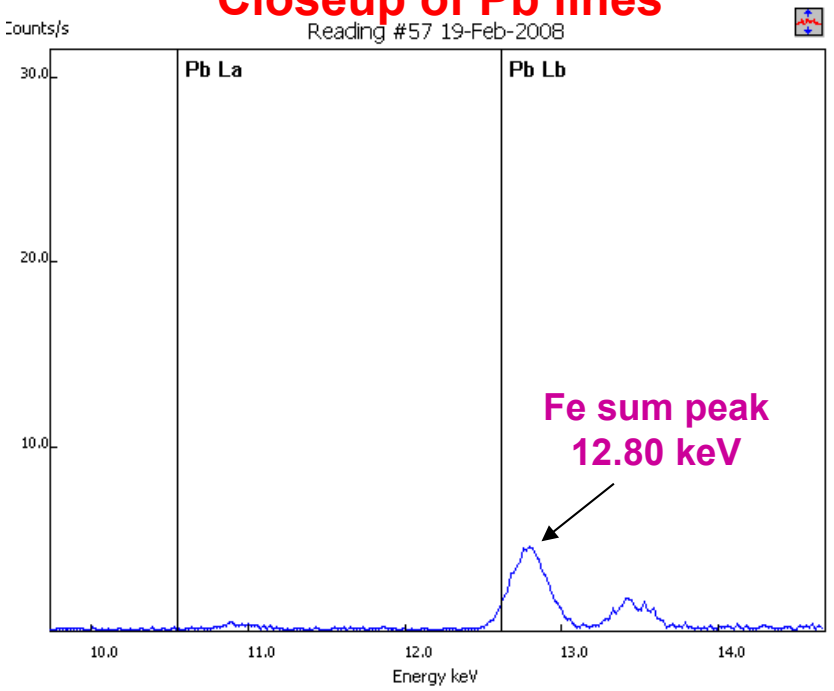
QUALITATIVE ANALYSIS

False positive for Pb in baby food cap

Spectrum



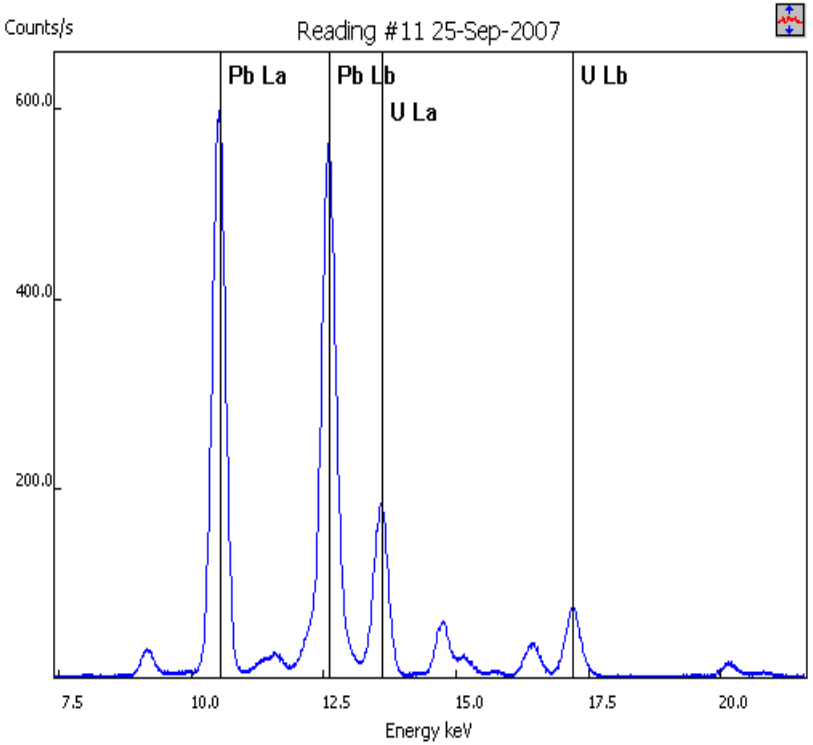
Closeup of Pb lines



- **User acquired sample spectrum near lid (>10% Fe), which gave Fe sum peak at 6.40 keV * 2 photons = 12.80 keV**
- **Vendor algorithm incorrectly identified Pb in this sample at over 2000 ppm (detection and quantitation based on signal at the Pb L_β line at 12.61 keV, zero intensity of Pb L_α line at 10.55 keV not considered by algorithm)**
- **Be wary of analyzer software and be sure to avoid potential false positives such as this by evaluating the spectrum to confirm the presence of an element**

QUALITATIVE ANALYSIS

False negative for U in tableware



- Vendor algorithm did not identify U in this sample (algorithm not intended to attempt this identification of this and other relatively uncommon elements)
- Lack of manual interpretation of the spectrum of a product containing only U would have led to the assumption that it was safe
- Be wary of analyzer software and be sure to avoid potential false negatives such as this by evaluating the spectrum to identify unexplained peaks

CONCLUSIONS ON QUALITATIVE ANALYSIS

Vendor software on commercial XRF analyzers are usually reliable in identifying which elements are present in a sample, but are not foolproof and an occasional false positive or false negative is possible

FALSE POSITIVES (element detected when not present)

- Due to limitations in the vendor software, which make not take into account line overlaps, sum peaks, escape peaks
- **Users must confirm positive detection of an element based on the observation of two peaks centered within ±0.05 keV of the tabulated line energies for that element at the proper intensity ratio (5:1 for K lines, 1:1 for L lines)**

FALSE NEGATIVES (element not detected when present)

- Due to limitations in the analyzer software, which may not be set up to detect all possible elements in the periodic table
- Unlikely occurrence for toxic elements such as As, Hg, Pb, and Se, more common for rare elements such as U, Th, and Os
- **Users must identify "non-detected" elements through manual interpretation of the spectrum**

QUANTITATIVE ANALYSIS

Issues to consider

Question: Are the element CONCENTRATIONS within the detection range of XRF (% to ppm levels)?

Answer: ***Define the problem, research sample composition, or take a measurement***

Question: What sort of SAMPLE PREP is required (can samples be analyzed as is or do they need to be ground up)?

Answer: ***Consider sample - is it homogeneous?***

Question: For SCREENING PRODUCTS, are semi-quantitative results good enough? For example, if percent levels of a toxic element are found in a supplement, is this sufficient evidence to detain it or to initiate a regulatory action?

Question: For ACCURATE QUANTITATIVE ANALYSES, what is the most appropriate calibration model to use for the samples of interest (Compton Normalization, Fundamental Parameters, empirical calibration, standard additions)?

TYPES OF CALIBRATION MODELS

VISUAL OBSERVATION (rough approximation, depends on many variables)

- Peak intensity >100 cps corresponds to concentrations >10,000 ppm (% levels)
- Peak intensity of 10-100 cps corresponds to concentrations of ~100-1000 ppm
- Peak intensity of 1-10 cps corresponds to concentrations ~10-100 ppm
- Peak intensity < 1 cps corresponds to concentrations ~1-10 ppm

FUNDAMENTAL PARAMETERS (aka FP or alloy mode)

- Uses iterative approach to select element concentrations so that modeled spectrum best matches samples spectrum (using attenuation coefficients, absorption/enhancement effects, and other known information)
- Best for samples containing elements that can be detected by XRF (i.e., alloys, well characterized samples, and samples containing relatively high concentrations of elements)

COMPTON NORMALIZATION (aka CN or soil mode)

- Uses "factory" calibration based on pure elements (i.e., Fe, As_2O_3) and ratioing the intensity of the peak for the element of interest to the source backscatter peak to account for differences in sample matrices, orientation, etc.
- Best for samples that are relatively low density (i.e., consumer products, supplements) and samples containing relatively low concentrations of elements (i.e., soil)

OTHER MODES – thin film/filters, RoHS/WEEE, pass/fail, etc.

- Beyond scope of these training materials

TYPES OF CALIBRATION MODELS

EMPIRICAL CALIBRATION

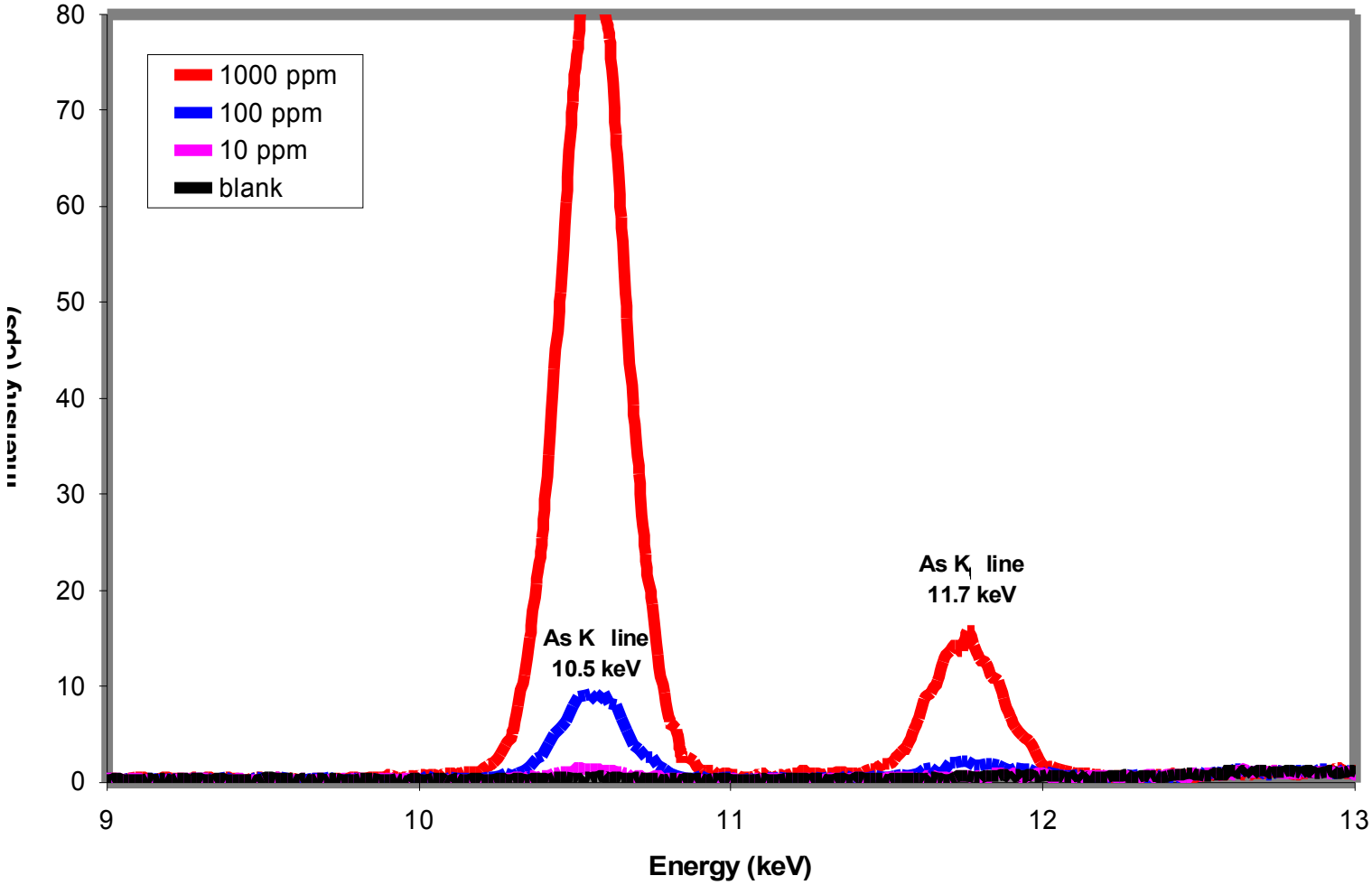
- Involves preparation of authentic standards of the element of interest in a matrix that closely approximates that of the samples
- Provides more accurate results than factory calibration and Compton Normalization
- Note that the XRF analyzer can be configured and used with this type of calibration to give more accurate results for the elements and matrices of interest
- Usually reserved for laboratory analyses by trained analysts, using a high purity metal salt containing the element of interest, an appropriate matrix, homogenization via mixing or grinding

STANDARD ADDITIONS

- Involves adding known amounts of element of interest into the sample
- Provides most accurate results as the standards are prepared in the sample matrix as the sample
- Usually reserved for laboratory analyses by trained analysts, and even then used only as needed as this is labor intensive and time consuming

EFFECT OF CONCENTRATION

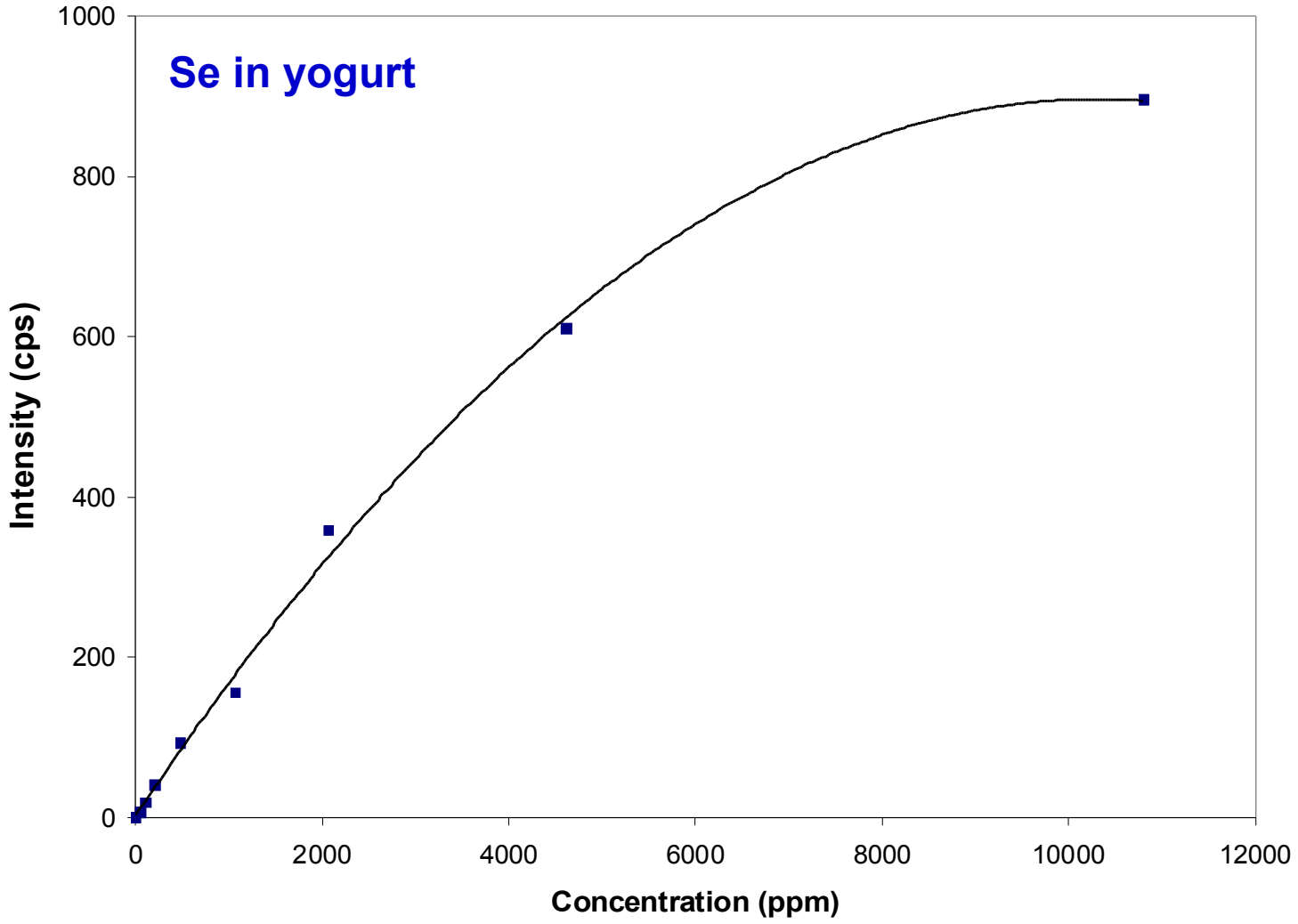
Spectra of As standards in cellulose



- Intensity is proportional to concentration
- Detection limits depend on element, matrix, measurement time, etc.
- Typical detection limits are as low as 1 part per million (ppm)

PEAK INTENSITY VS CONCENTRATION

Linearity falls off at high concentrations

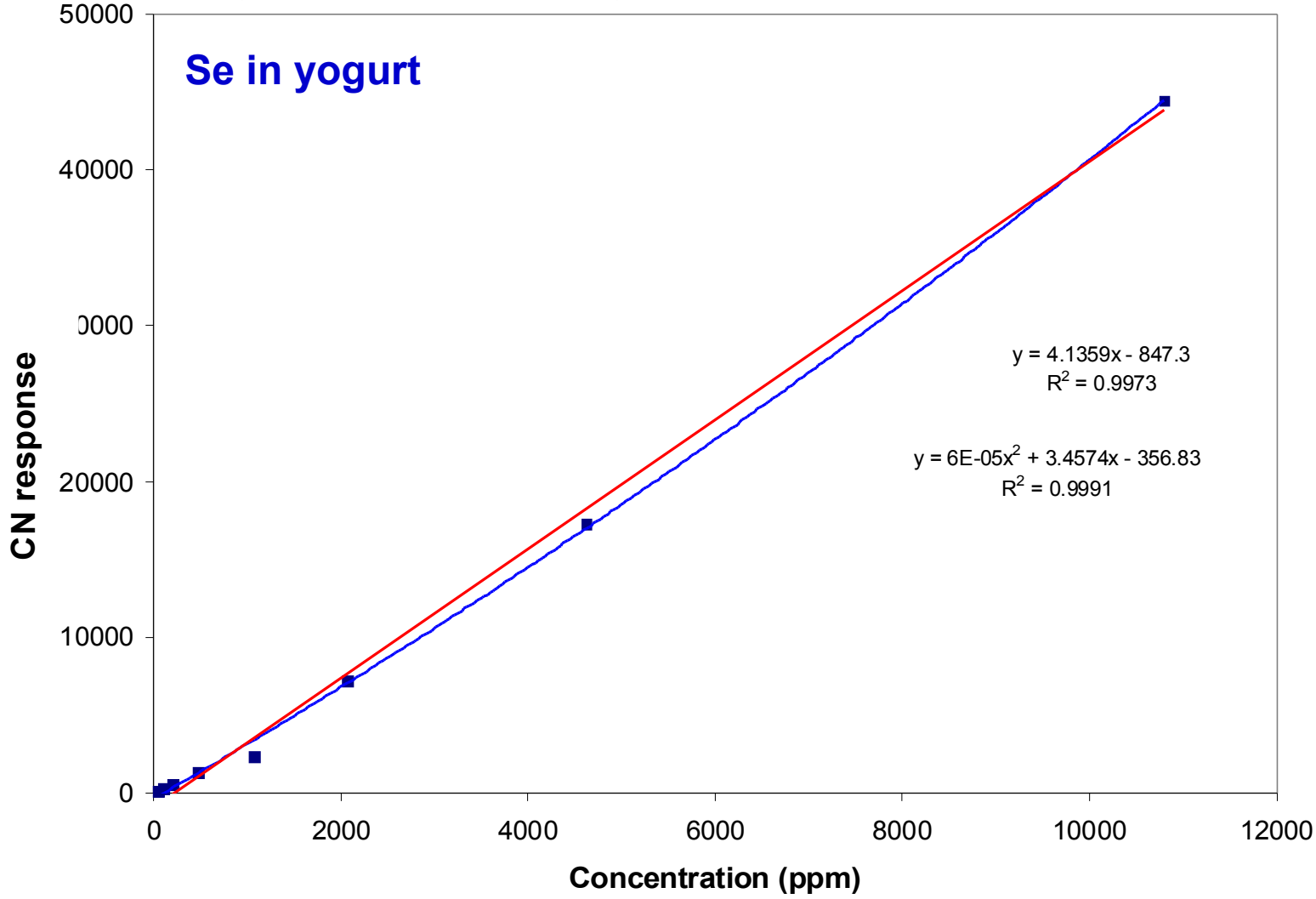


- **Response becomes nonlinear between 1000-10,000 ppm**
- **Use of Compton Normalization will partially correct for this**

P.T. Palmer et al, DXC, 2008 (Se in yogurt, Innov-X alpha 2000)

COMPTON NORMALIZED INTENSITY VS CONC.

Linearity improves through use of "internal standard"

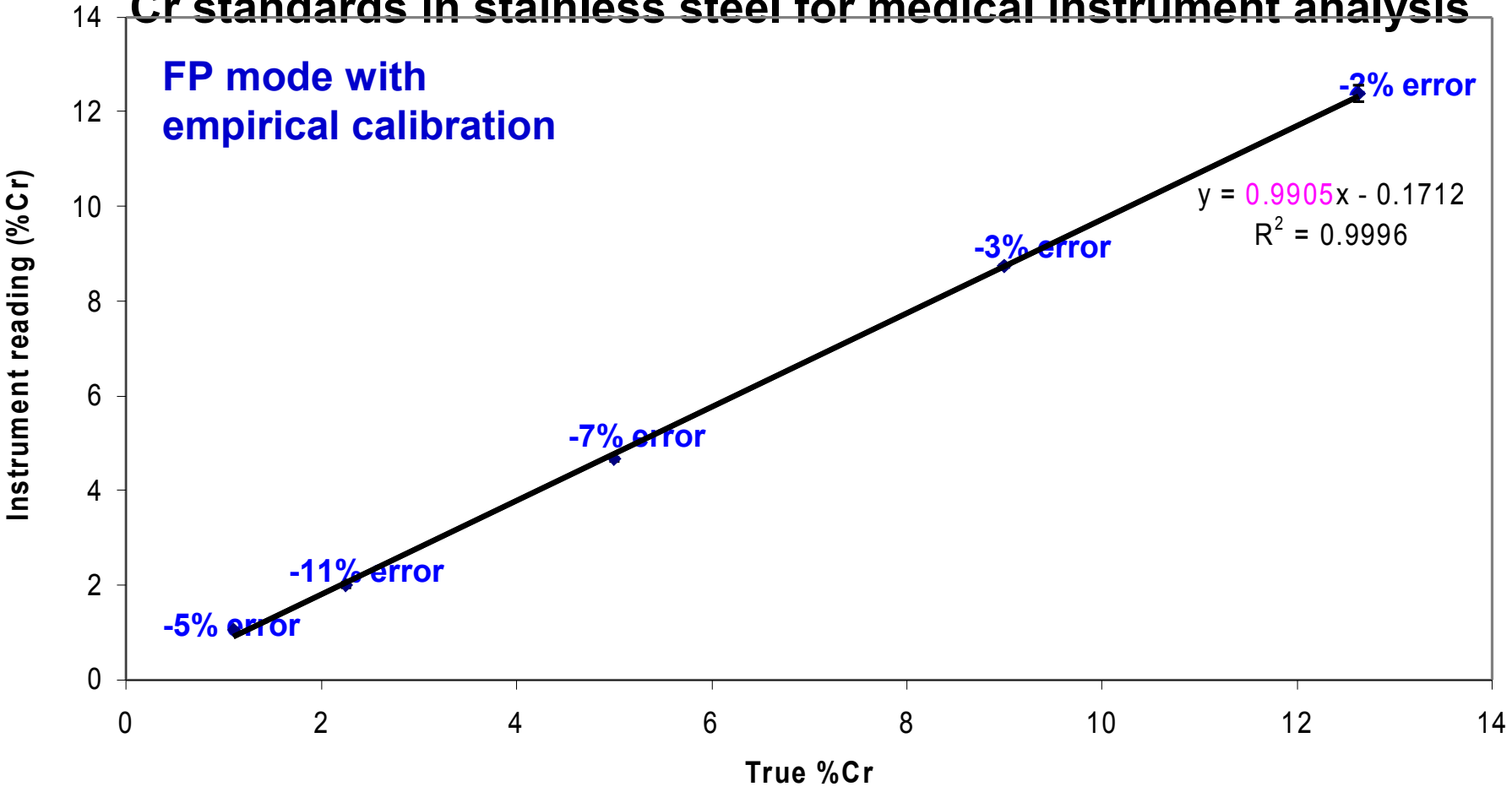


- **Use of Compton Normalization (X-ray tube source backscatter from sample) *partially* corrects for self absorption and varying sample density**

P.T. Palmer et al, DXC, 2008 (Se in yogurt, Innov-X alpha 2000)

QUANTITATIVE ANALYSIS AT HIGH CONC'S

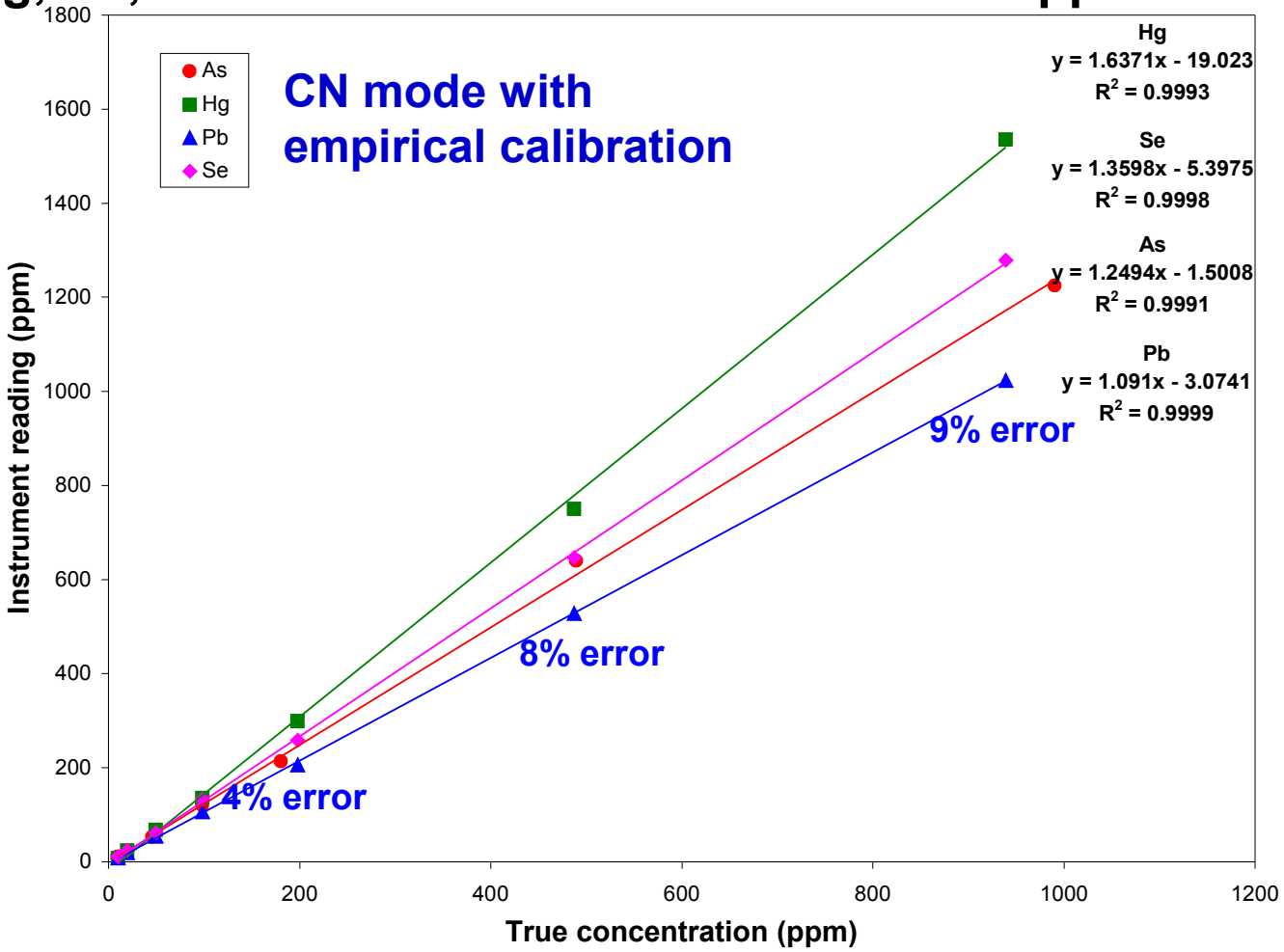
Cr standards in stainless steel for medical instrument analysis



- Although Fundamental Parameters based quantitation gives fairly accurate results, it also gives determinate error (consistently negative errors)
- Determination of Cr in surgical grade stainless steel samples using an XRF analyzer calibrated with these standards gave results that were *statistically equivalent to flame atomic absorption spectrophotometry*
- *For determining % levels of an element, use Fundamental Parameters mode*

QUANTITATIVE ANALYSIS AT LOW CONC'S

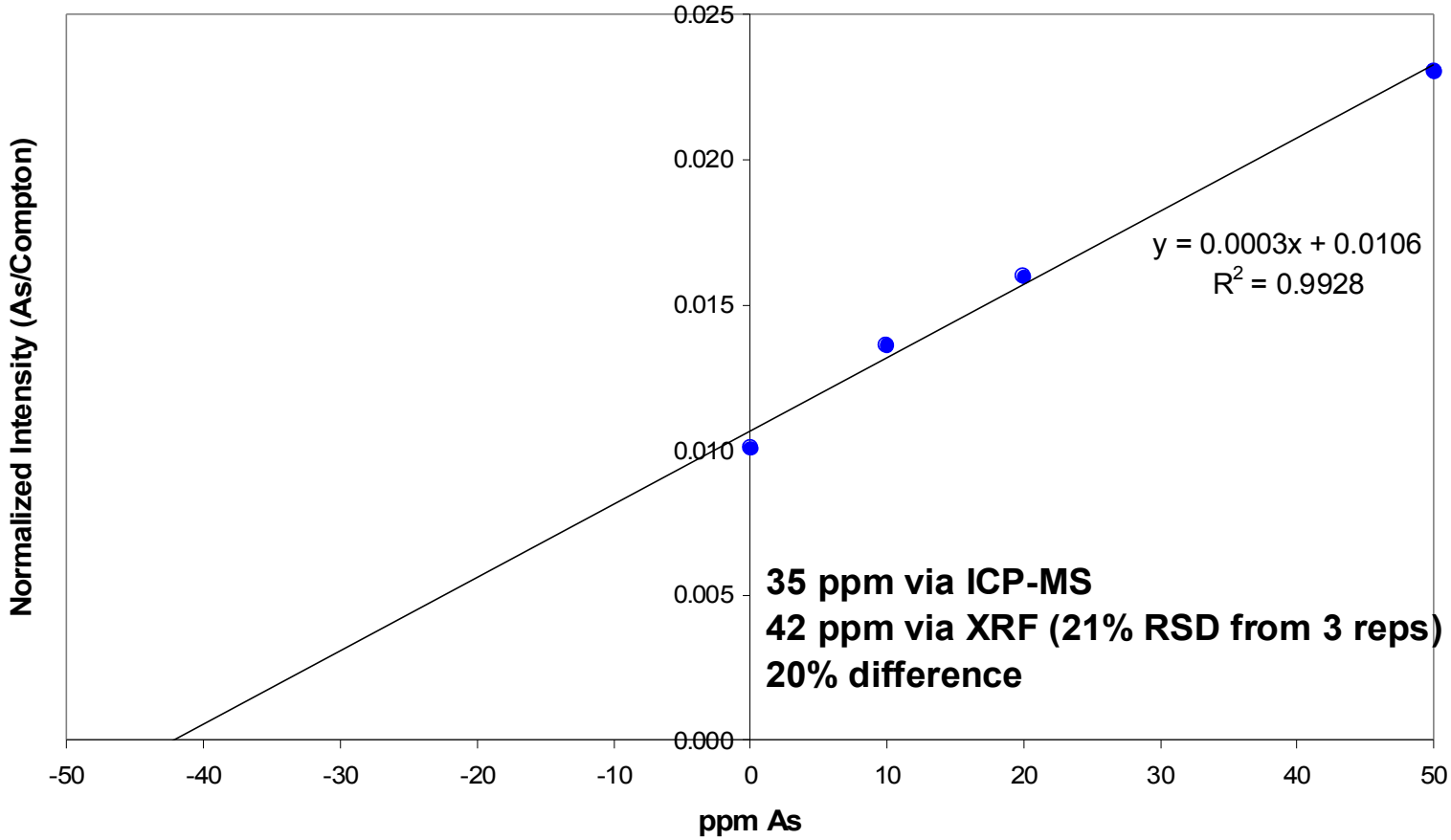
As, Hg, Pb, and Se standards in cellulose for supplement analysis



- Although Compton Normalization based quantitation gives fairly accurate results, it can also give significant determinate error (slopes > 1)
- Determination of Pb in supplements using an XRF analyzer calibrated with these standards gave results that were *statistically equivalent to ICP-MS*
- *For determining ppm levels of an element, use Compton Norm. mode*

STANDARD ADDITIONS METHOD

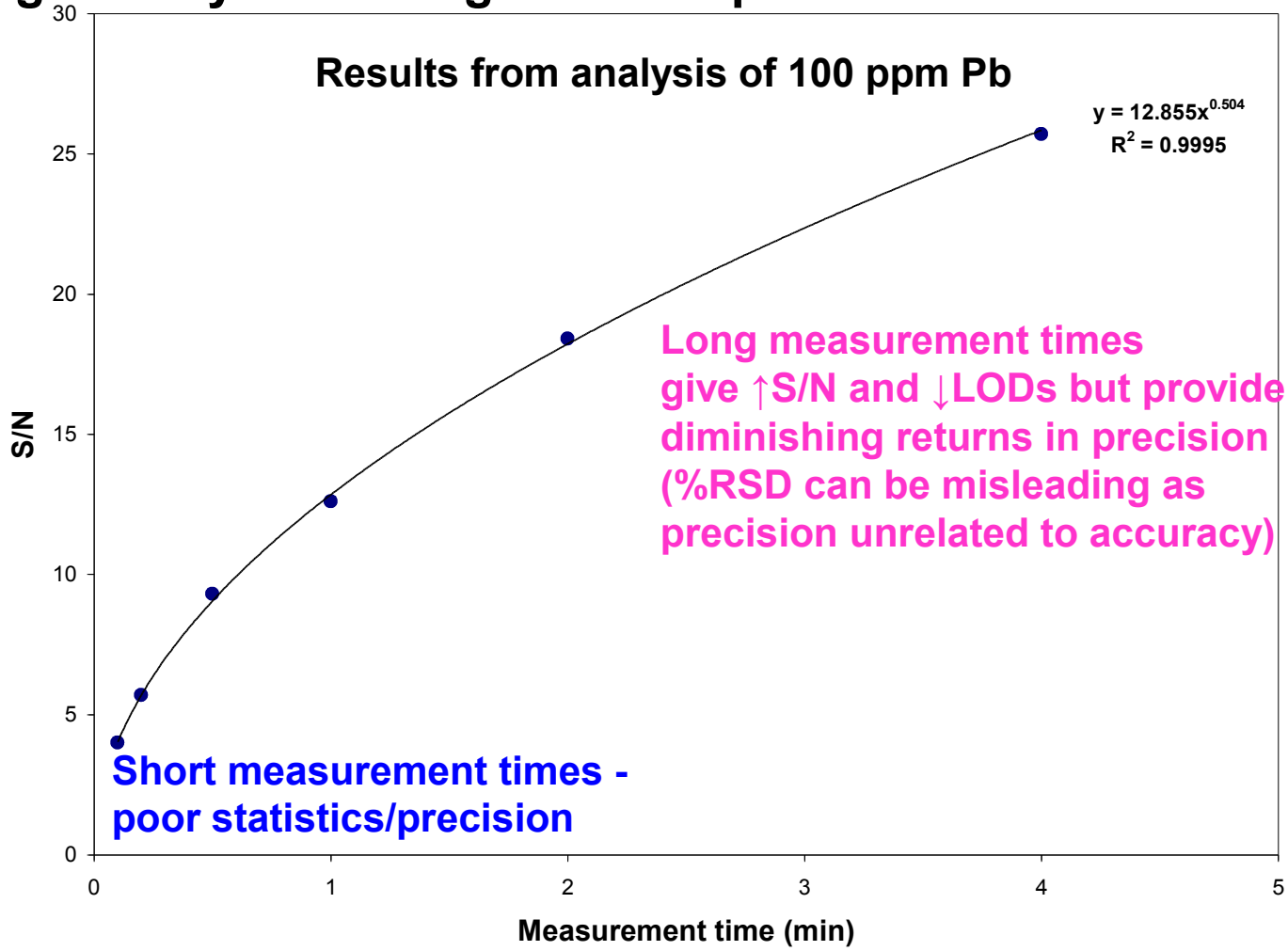
Determination of As in grapeseed sample



- **Typically gives more reliable quantitative results as this method involves matrix matching (the sample is "converted" into standards by adding known amounts of the element of interest)**
- **This process is more time consuming (requires analysis of sample "as is" plus two or more samples to which known amounts of the element of interest have been added)**

EFFECT OF MEASUREMENT TIME

Longer analysis times give better precision and lower LODs



- S/N = mean signal / standard deviation of instrument response (noise)
- As per theory, S/N is proportional to square root of measurement time
- 1-2 min measurement gives a good compromise between speed and precision
- Longer measurement times give better S/N and lower LODs

CONCLUSIONS ON QUANTITATIVE ANALYSIS

For field applications, the sample is often analyzed "as is" and some accuracy is sacrificed in the interest of shorter analysis times and higher sample throughput, as the more important issue here is sample triage (identifying potential samples of interest for more detailed lab analysis)

- **Use FP mode to analyze samples that contain % levels of elements**
- **Use CN mode to analyze samples that contain ppm levels of elements and have varying densities**

For lab applications, more accurate quantitative results are obtained by an empirical calibration process

- **Grind/homogenize product to ensure a representative sample**
- **Calibrate the analyzer using standards and/or SRMs**
- **Use a calibration curve to compute concentrations in samples**
- **When suitable standards are not available or cannot be readily prepared, consider using the method of standard additions**

For either mode of operation, getting an accurate number involves much more work than implied in the "point and shoot" marketing hype of some XRF manufacturers

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FOUR KEY ADVANTAGES OF XRF FOR MANY APPLICATIONS

SIMPLICITY

- Relatively simple theory, instrument, and spectra (versus IR, MS, NMR)

MINIMAL SAMPLE PREP

- For many screening applications, samples can often be analyzed "as is" with minimal sample processing
- For accurate quantitative analysis, samples must be ground up and homogenized (faster and easier than acid digestion required for conventional atomic spectrometry methods)

TYPICAL ANALYSIS TIMES ON THE ORDER OF 1 MINUTE

- For determining % levels of an element (which typically gives high count rates), measurement times can be as short as a few seconds
- For ppm-level detection limits, measurement times on the order of 1-10 minutes are needed

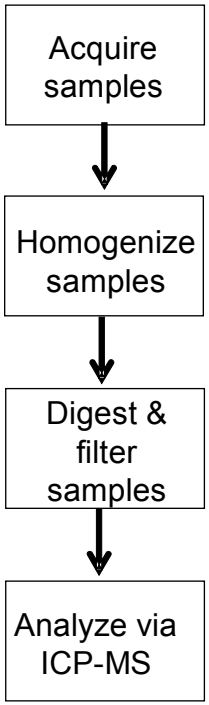
PORTABILITY

- Instrument can be brought to the samples

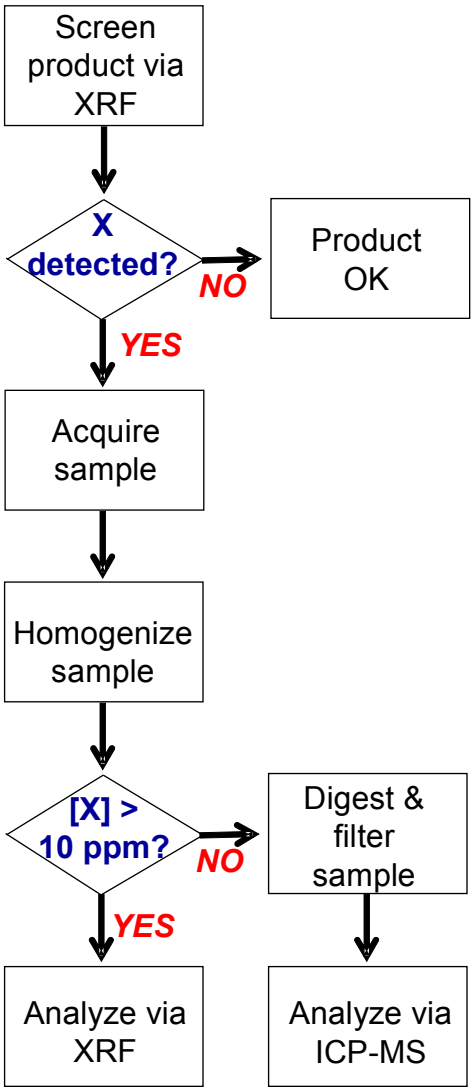
ANALYTICAL PROCESS STREAM

- Use XRF for "**sample triage**" (sort into "detects" and "non-detects")
- Avoid wasting time trying to quantify non-detectable levels of a toxic element with more time consuming methods such as ICP-MS
- Avoid problems trying to quantify % levels of a toxic element with a very sensitive technique such as ICP-MS (contaminating digestion vessels, glassware, instrument, etc. in low-level process stream)
- **Perform accurate quantitative analysis (via XRF or ICP-MS) where warranted**

Typical analysis protocol



More intelligent analysis protocol



TOXIC ELEMENTS IN TABLEWARE

Pb and other elements are still causing problems

Pb and U
detected in ceramic material
imported from Mexico

Pb, Co, and other elements
detected in individual pigments
in plate imported from China

- **Ceramic plates may contain toxic elements that can leach into food**
- **XRF can be used to quickly identify elements and their concentrations in tableware, glazes, and base ceramic material, and food**

Pb IN IMPORTED TABLEWARE AND FOOD PRODUCTS

"The **prevalence of elevated blood lead levels was significantly higher** in 1 of the 3 clinics (**6% among screened children and 13% among prenatal patients**)"

"**Consumption of foods imported from Oaxaca was identified as a risk factor for elevated blood lead levels** in Monterey County, California."

Handley et al, Am J Public Health, May 2007, Vol 97, No. 5, pp 900-906

"…the source was found to be related to contamination of foods in Mexico that was inadvertently transported to California through a… practice, called '**envios**' (Spanish for send or transport) … the frequent transport of prepared foods from Mexico to California. Envios in fact are 'mom and pop' express air transport businesses in which **foods are sent from home in Oaxaca to home in California**, often on a daily basis. Unfortunately, it was discovered that some of the foods contained lead. The **as yet unidentified sources of the lead are currently undergoing investigation**."

Handley et al, Intl J of Epidemiology, 2007, 36, pp 1205–1206

Pb IN IMPORTED TABLEWARE AND FOOD PRODUCTS

"An interdisciplinary investigation…was undertaken to determine the contamination source and pathway of an on-going **outbreak of lead poisoning among migrants originating from Zimatlán, Oaxaca, Mexico and living in Seaside, California**, and among their US-born children…

The focus in the present work concentrates on the Oaxacan area of origin of the problem in Mexico, and **two potential sources of contamination were investigated: wind-borne dusts from existing mine residues as potential contaminants of soil, plant, and fauna; and food preparation practices using lead-glazed ceramic cookware…**

The **results indicated significant presence of lead in minewastes, in specific foodstuffs, and in glazed cookware, but no extensive soil contamination was identified.** In-situ experiments demonstrated that **lead incorporation in food is made very efficient through grinding of spices in glazed cookware, with the combination of a harsh mechanical action and the frequent presence of acidic lime juice,** but without heating, resulting in high but variable levels of contamination."

Villalobos et al, Science of the Total Environment, in press

Pb IN TABLEWARE

Samples from Monterey County, CA

Analysis via handheld XRF calibrated with Pb standards

pitcher, green-grey glaze, Central Market Zimatlan, Mexico	**10%**
bean pot, grey glaze, Central Market Zimatlan, Mexico	**11%**
small bowl (chimolera), green glaze, Central Market Zimatlan, Mexico	**7%**
incense burner, green glaze, 3-legged, El Milagro	**8%**
clay pot, red glaze, 12" diam, smooth inside, El Milagro	**11%**
clay pot, green glaze, 10" diam, for grating, El Milagro	**10%**

small bowl (chimolera), envios julietta	**7%**
bowl, green glaze, lace on inside edge	**48%**
bird dish, green glaze	**37%**
dish, unglazed	**40%**
large brown bowl, unglazed (from Celeste)	**26%**
large pitcher (from Celeste)	**33%**
small decorative bowl, red glaze	**1%**
pottery, black glaze	**66 ppm**

H. Gregory, P.T. Palmer, manuscript in prep

Pb IN FOOD AND NEW TABLEWARE

Samples from Monterey County, CA
Analysis via handheld XRF calibrated with Pb standards

chapulines, ag (Emilio's sisters)	**406 ppm**
chapulines, ag (extended Aquino family members)	**387 ppm**
chapulines, harvested in Aug, Central Market Zimatlan, Mexico	**131 ppm**

Newer “Pb-free” glaze may not be safe either

new glaze bowl, 6" diam, *unglazed bottom*	**98 ppm**
new glaze bowl, 6" diam, *glazed portion*	**102 ppm**
new glaze bowl, 10" diam, 2-handled, widemouth	**162 ppm**
new glaze bowl, 10" diam, 2-handled, narrow mouth	**96 ppm**
new glaze pitcher 1-handled	**276 ppm**

Cu, Zn not detected!

43% Cu, 28% Zn

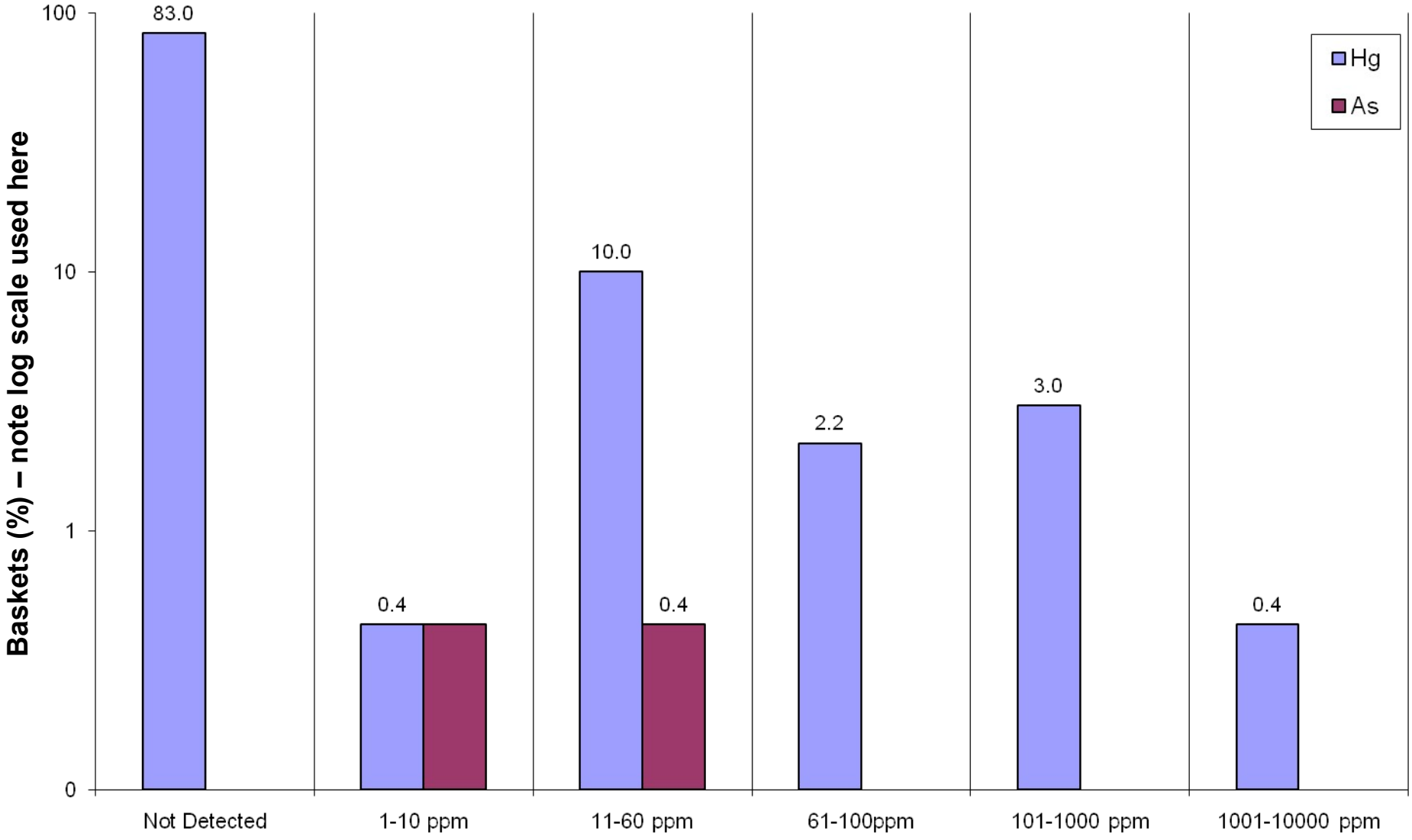
H. Gregory, P.T. Palmer, manuscript in prep

MUSEUM ARTIFACTS PRESERVED WITH As AND Hg

Ideal for nondestructive testing via handheld XRF

RESULTS FROM BASKET COLLECTION

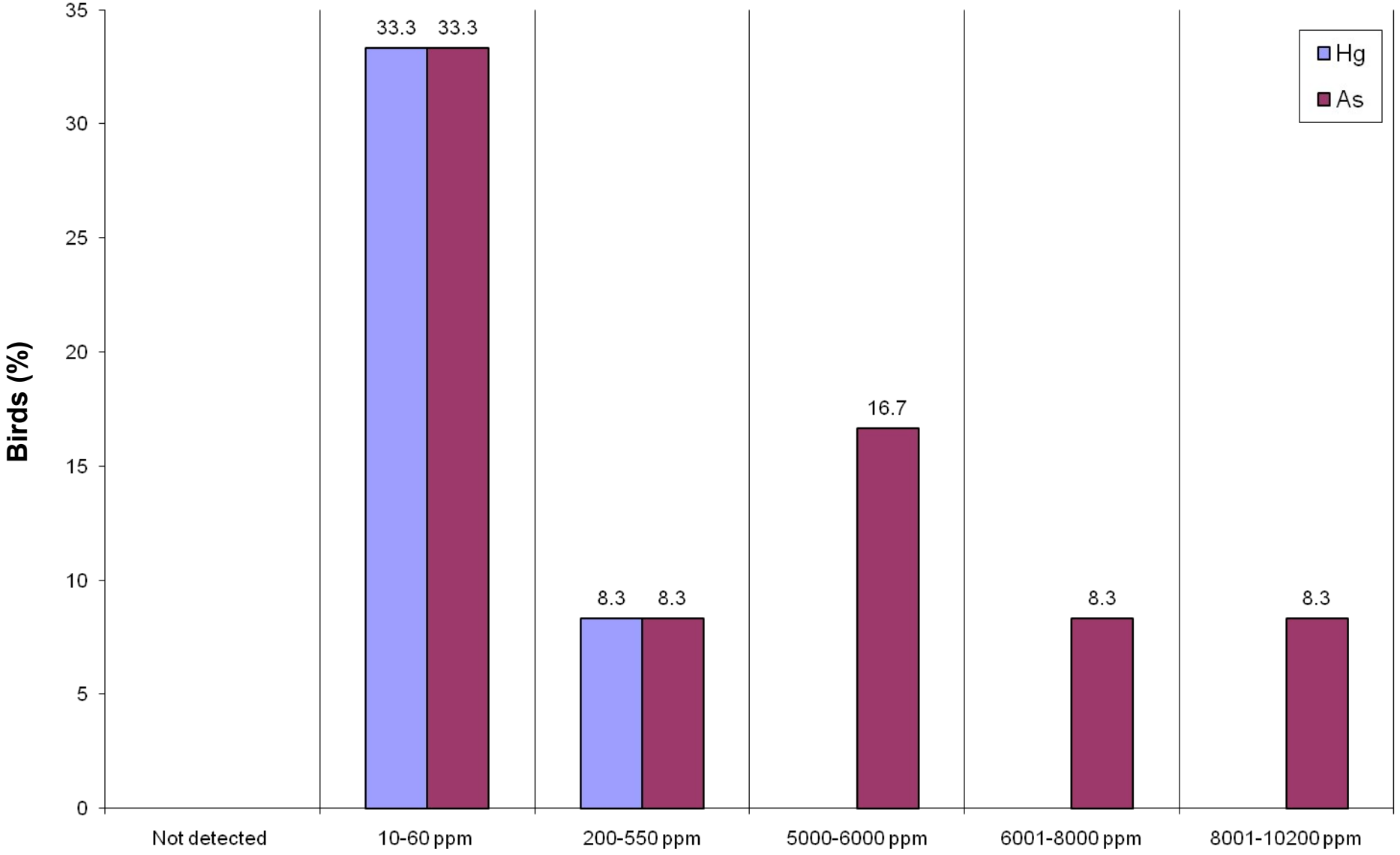
Handheld XRF calibrated with Hg and As standards
Detectable Hg contamination on 17% of the baskets



K. Cross, P.T. Palmer, manuscript in prep

RESULTS FROM BIRD COLLECTION

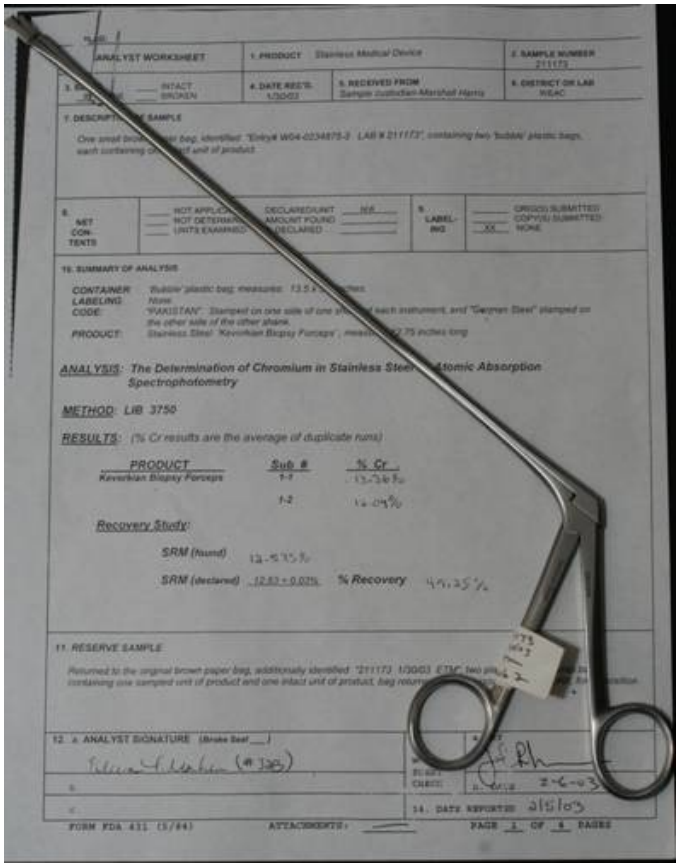
Handheld XRF calibrated with Hg and As standards
Significant As contamination on most of the birds



K. Cross, P.T. Palmer, manuscript in prep

DETERMINATION OF Cr IN STAINLESS STEEL

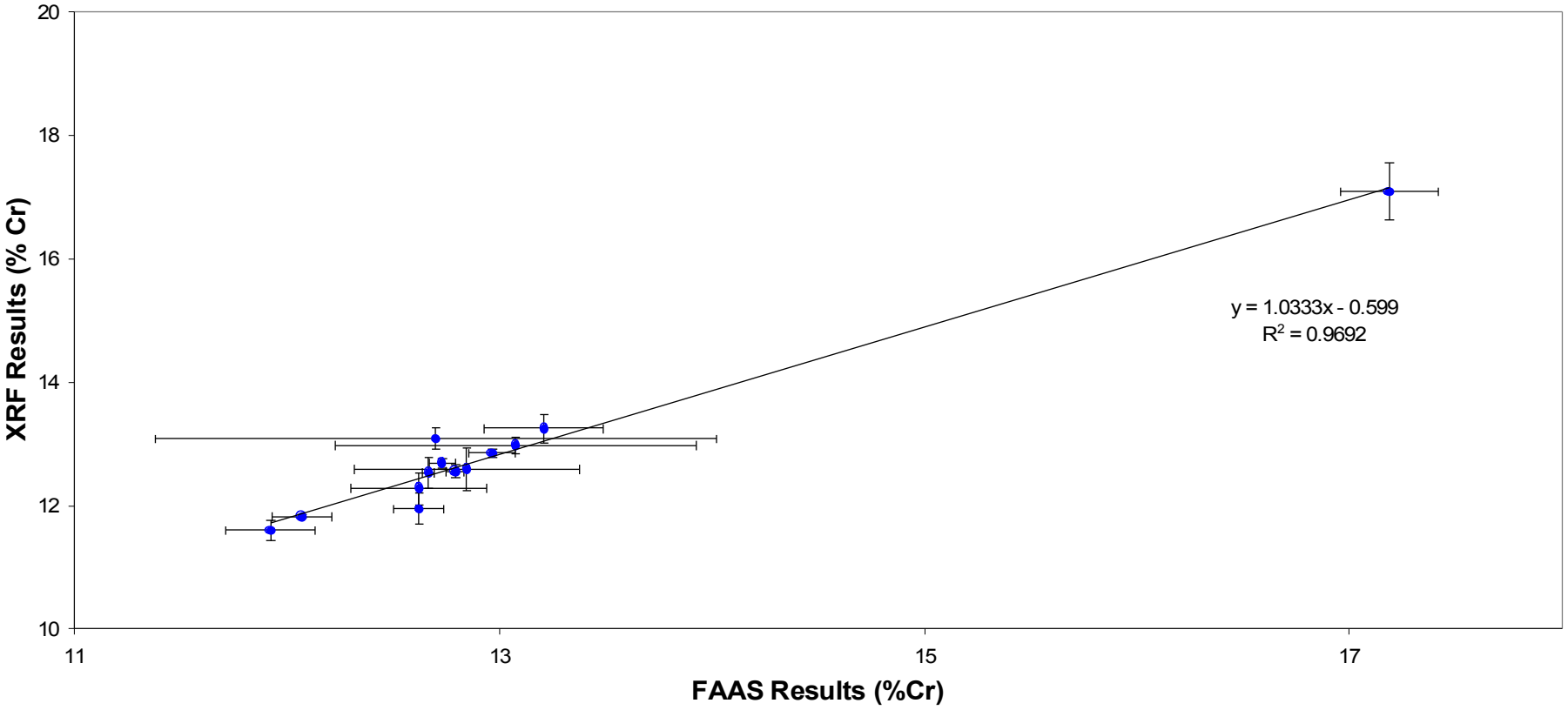
Handheld XRF analysis of Kervorkian-designed biopsy forceps



- **Atomic absorption method gave 12.7% Cr (difficult prep and digestion, >1-day effort)**
- **XRF analysis gave 12.8% Cr and correctly identified alloy (no sample prep, FP mode, empirical calibration with Cr standards, <1 min reading)**
- **Results used to confirm labeling requirements for Cr content in surgical products used in medical applications**

P.T. Palmer et al, "Rapid Determination of Cr in Stainless Steel via XRF", FDA Lab Information Bulletin, July 2006.

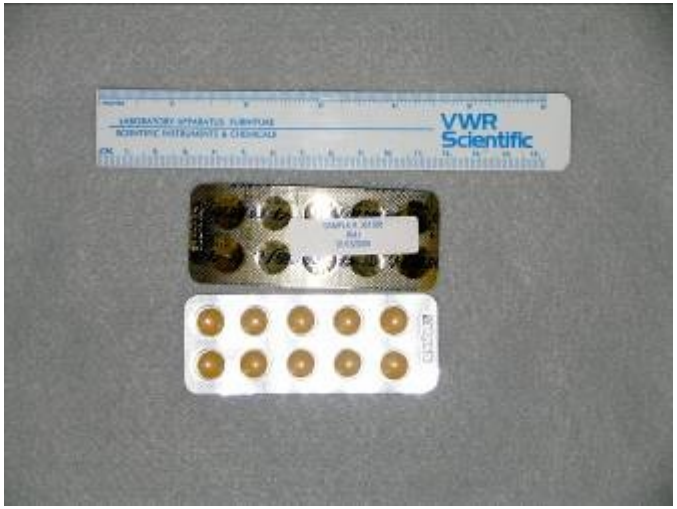
XRF VS ATOMIC ABSORPTION FOR Cr IN STAINLESS STEEL



- **t test indicates no significant differences at the 95% confidence level between handheld XRF and conventional Atomic Absorption Spectrophotometry method**
- **Such data demonstrate that XRF <u>can</u> give accurate quantitative results**

P.T. Palmer et al, FDA Lab Information Bulletin, August 2010.

CHINESE HERBAL MEDICINE - Niuhuang Jiedu Pian



- **Product manufactured in China (Cow yellow detoxification tablet), Intended to treat mouth ulcers, relieve tooth aches, reduce fever, and "release toxins", product import document indicated that As in the form of realgar (As_4S_4)**

- **ICP-MS showed 6.85% As (note low value here versus XRF may be due to inability of acid digestion procedures to dissolve realgar)**

- **Handheld XRF showed 11.7% As in product (Compton Normalization mode, empirical calibration with As standards, diluted sample into range of standards)**

- **Recommended max dose of 9 tablets per day is equivalent to consumption of 0.173 g of As (minimum lethal dose ~0.130 g*)**

P.T. Palmer et al, J Ag. Food Chem, 57 (2009) 2605. *http://www.atsdr.cdc.gov/toxprofiles/tp2.pdf, p. 60, 127.

TOXIC ELEMENTS IN SUPPLEMENTS

- Dietary supplement sales in the U.S. surpassed $21 billion in 2006 and 60% of people use them on a daily basis
- The Dietary Supplement Health and Education Act (DSHEA) does not require manufacturers to perform any efficacy or safety studies on dietary supplements
- FDA's Current Good Manufacturing Practice (cGMP) requirements for Dietary Supplements provides no recommended limits for specific contaminants
- Numerous studies have reported the presence of toxic elements in a large numbers of domestic and imported supplement products
- Concerns for consumer safety have led to a Canadian ban on imports of Ayurvedic medicines in 2005 and a call for more testing and better regulation of these products
- Clearly XRF is an ideal tool for this application

AYURVEDIC MEDICINES – Pushpadhanwa

- **Ayurvedic medicine *Pushpadhanwa* (ironically, a fertility drug), label information indicates that it contains the following:**
  - **Rasasindoor = Pure mercury and sulfur**
  - **Nag Bhasma = Lead oxide (ash)**
  - **Loha Bhasma = Grom oxide**
  - **Abhrak Bhasma = Mica oxide**

- **Santa Clara County Health Dept issued a press release (Aug 2003) regarding this product which caused two serious illnesses and a spontaneous abortion**

- **Atomic absorption analysis by private lab showed 7% Pb in this product**

- **Handheld XRF analysis showed 8% Pb and 7% Hg (Compton Normalization mode, empirical calibration with authentic standards, diluted sample into range of standards)**

P.T. Palmer et al, J Ag. Food Chem, 57 (2009) 2605.

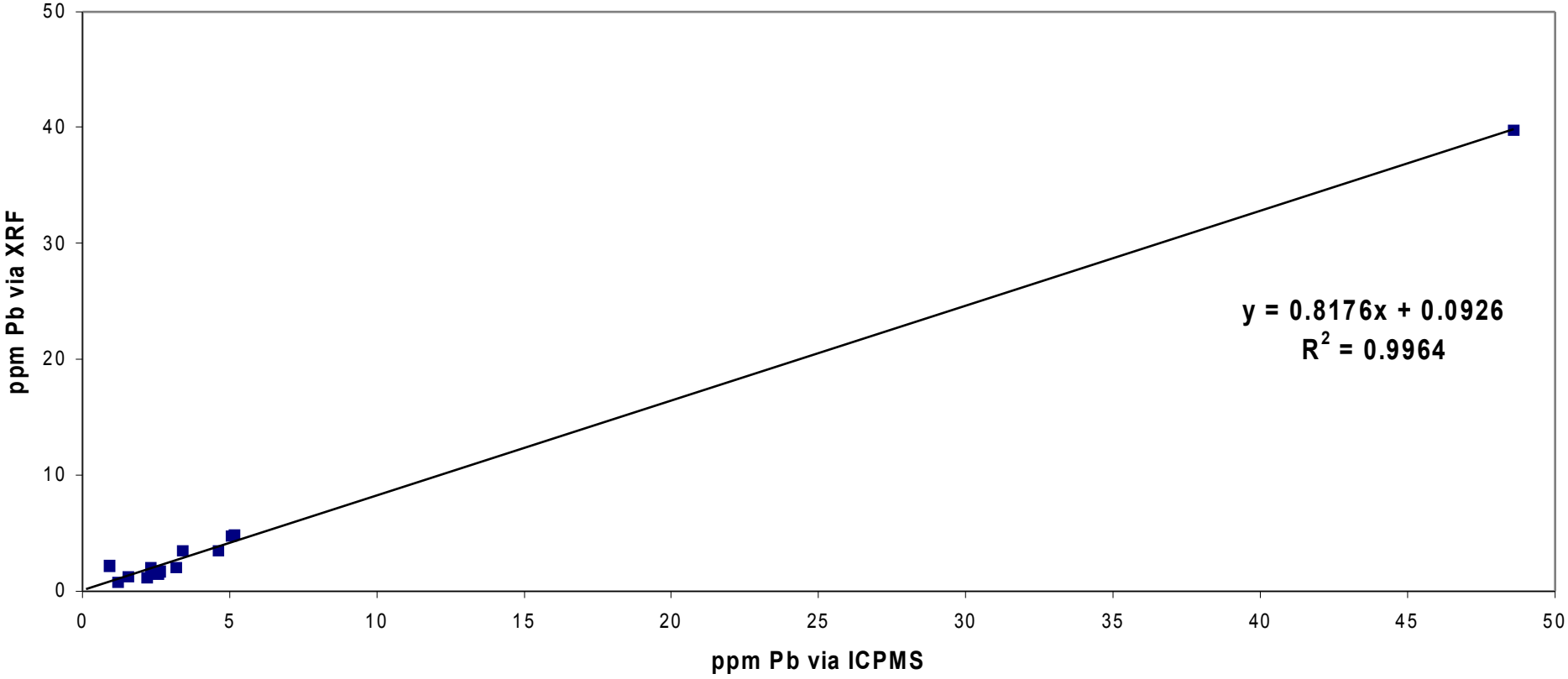
IMPORTED AND DOMESTIC SUPPLEMENTS

- **Dolan, Capar, et al (FDA/CFSAN) reported on determination of As, Hg, and Pb in dietary supplements via microwave digestion followed by high resolution ICP-MS** Dolan et al, J Ag & Food Chem, 2003, 51, 1307.
- **A subset of these samples (28) were the focus of a study to compare and evaluate several different XRF analysis methods**

- **This represents a very challenging application for XRF due to**
  - **Low levels of toxic elements in these samples (highest was 50 ppm)**
  - **Tremendous variability of sample matrices and preparation of appropriate standards for an empirical calibration (cellulose was used to approximate the predominantly organic content of the samples)**
  - **As and Pb spectral overlaps and co-occurrence of both in some samples**

- **Our goal was to evaluate XRF in two different modes of operation**
  - **Screening products "as is" using an empirically calibrated handheld XRF (results not included in this presentation)**
  - **Accurate quantitative analysis of homogenized products using an empirically calibrated lab-based XRF (completely automated data acquisition, calibration, quantitative analysis, and report generation)**

XRF VS ICP-MS FOR TOXIC ELEMENTS IN SUPPLEMENTS



- **t test indicates no significant differences at the 95% confidence level between lab-grade XRF and conventional ICP-MS method**
- **Such data demonstrate that XRF <u>can</u> give accurate quantitative results (impressive considering most samples contain these elements at concentration that are very close to the detection limit)**

P.T. Palmer et al, FDA Lab Information Bulletin, August 2010.

OUTLINE

1. **INTRODUCTION**
   - The electromagnetic spectrum and X-rays
   - Basic theory of XRF and simple XRF spectra
   - Different types of XRF instruments

2. **INTERPRETATION OF XRF SPECTRA**
   - XRF spectra of different elements
   - Limited resolution and overlapping peaks
   - Artifact peaks

3. **QUALITATIVE AND QUANTITATIVE ANALYSIS**
   - Confirmation of detection of an element
   - Different calibration models
   - Example calibration curves

4. **APPLICATIONS OF XRF**
   - Screening for toxic elements in large numbers of samples
   - Accurate quantitative analysis of target elements in various matrices

5. **CONCLUSIONS**
   - XRF advantages and limitations
   - References and additional reading

ADVANTAGES OF XRF

Selectivity: **True multi-element analysis** (from S to U, ~80 different elements)
Measures total element concentration (independent of chemical form)

LODs: **1 to 10 ppm at best** (depends on source, element, matrix, etc.)

Linearity: **Linear response over 3 orders of magnitude** (1-1000 ppm)

Accuracy: **Relative errors ~ 50% with factory calibrated instrument**
Relative errors < 10% using authentic standards for calibration

Precision: **RSDs < 5%** (must have homogeneous sample)

Speed: **Minimal sample prep** (analyze "as is" or homogenize and transfer to cup)
Fast analysis times (typically seconds to minutes)

Cost: **$25,000-$50,000** for field portable instrument
Far less expensive per sample than FAAS, GFAAS, ICP-AES, and ICP-MS

Miscellaneous: **Simple** (can be used by non-experts in the field)
Nondestructive (sample can be preserved for follow up analysis)
Field-portable instruments can operate under battery power for several hours

LIMITATIONS OF XRF

Selectivity: ***Interferences* between some elements** (high levels of one element may give a false positive for another due to overlapping emission lines and limited resolution of ~0.2 keV FWHM)

No info on *chemical form* of element (alternate technique required for speciation)

Detection Limits: **Must use alternate technique to measure *sub-ppm levels*** (TXRF, GFAAS, ICP-AES, ICP-MS)

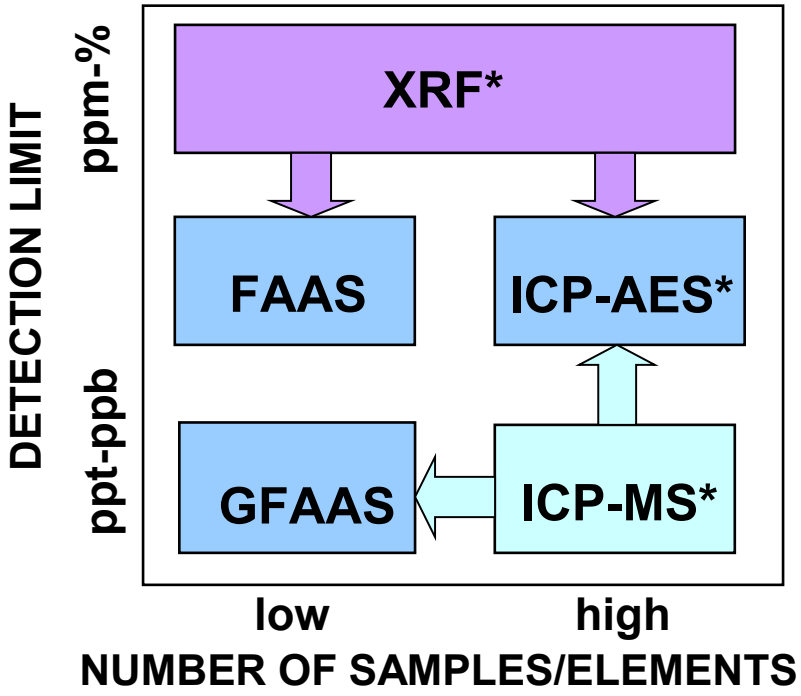
Accuracy: **XRF is predominantly a surface analysis technique** (X-rays penetrate few mm into sample)

To get more accurate results, one must *homogenize the samples* and *calibrate instrument response* using authentic standards

TRENDS IN ELEMENTAL ANALYSIS TECHNIQUES

XRF and ICP-MS are complementary

These techniques are replacing conventional atomic spectroscopy techniques such as FAAS and GFAAS



Technique	XRF	ICP-MS
Elements	Na-U	Li-U
Interferences	spectral overlaps, limited resolution	isobaric ions
Detection Limit	~1-10 ppm	~10 ppt (liquids) ~10 ppb (solid-0.1 g into 100 mL)
Sample prep	minimal (homogenization)	significant (digestion/filtration)
Field work	yes	not possible
Capital cost	$25-50K	$170-250K

SAFETY CONSIDERATIONS

- **XRF X-ray tube sources are far less intense than medical and dental X-ray devices**

- **When an XRF analyzer is used properly, users will be exposed to non-detectable levels of radiation**

Scenario/situation	**exposure**	**units**
Exposures from normal operation of XRF analyzer in sampling stand		
Left/right/behind analyzer	**<< 0.1**	mREM/**hour**
Exposures from background radiation sources		
Chest X-ray	**100**	mREM/**X-ray**
Grand Central Station	**120**	mREM/**year**
Airline worker	**1000**	mREM/**year**
Exposure limits set by regulatory agencies		
Max Permissible Limit during pregnancy	**500**	mREM/**9 months**
Max Permissible Limit for entire body	**5000**	mREM/**year**
Max Permissible Limit for an extremity (i.e., finger)	**50,000**	mREM
Exposures from unauthorized and unacceptable use of XRF analyzer outside sampling stand		
4 feet directly in front of analyzer window	**14**	mREM/**hour**
1 foot in front of analyzer window	**186**	mREM/**hour**
Directly in front of analyzer window	**20,000**	mREM/**hour**

REFERENCES AND ADDITIONAL READING

Good non-commercial website with XRF info

www.learnxrf.com

Excellent reference text on the subject matter

R. Grieken, A. Markowicz, Handbook of X-Ray Spectrometry, 2nd Ed., CRC Press, Boca Raton, FL, 2002.

Feature/Perspectives article on FDA applications of XRF

P.T. Palmer, R. Jacobs, P.E. Baker, K. Ferguson, S. Webber, "On the Use of Field Portable XRF Analyzers for Rapid Screening of Toxic Elements in FDA-Regulated Products", Journal of Agricultural and Food Chemistry, vol. 57, 2009, pp. 2605-2613.

EPA method based on XRF for soil analysis

EPA Method 6200 – Field Portable XRF for the Determination of Toxic Elements in Soils and Sediments (find at www.epa.gov)

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- Tom Sidebottom and Dr. Rod Asmundson (Lab Directors)
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- Thermo-Niton (Rich Phillips, Peter Greenland)

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DISCLAIMERS

The reference to any commercial materials, equipment, or process does not in any way constitute approval, endorsement, or recommendation by the FDA