Physics Methods in Art and Archaeology

Michael Wiescher

PHYS 178
Archaeologist in the 1920ties

Somewhere in South America
80 years later ---

in the Valley of the Kings, Egypt
Physics Tools & Technology

Danger & Adventure is gone …
Physics tools and modern technology dominate
the analysis of art and archaeological artifacts!
and worse (?):
biological & medical
techniques are at the horizon!

Be prepared!

Goal of course:
• Present a comprehensive overview of physics techniques
• Present examples for application of these techniques
1. The Physics Principles

1. Principles of physics tools and monitors
   - Must provide unique signature
   - Must be non-destructive or must require only limited sample size

2. General summary of tools
   a. Atomic and nuclear spectroscopy
      - Origin and nature of the electromagnetic spectrum
      - Atomic line spectroscopy in IR, optical, and UV
      - x-ray signatures
      - γ-ray signatures

   b. Radiation Origin and Radiation Laws
      - Nature of radiation
      - Production of radiation
      - Radiation decay laws
1.1. Goals and Purpose of Archaeometry

“Within archaeological artifacts there is a record to which an archaeologist is blind but which a physicists can hope to read”

(M.J. Aitken, Physics Report 1978)

To be able to “read” and analyze archaeological or historical artifacts, you need to probe the microstructure of the matter to determine it’s consistency and age. This requires non-destructive methods for material analysis and material dating which are provided by the tools developed for atomic and nuclear spectroscopy!
## Purpose of Material Analysis Techniques

<table>
<thead>
<tr>
<th>Artifact</th>
<th>Purpose of Material Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material Identification</td>
</tr>
<tr>
<td>Stone</td>
<td>mineral content</td>
</tr>
<tr>
<td>Obsidian</td>
<td>tracer elements</td>
</tr>
<tr>
<td>Marble</td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>hardness, element content, texture</td>
</tr>
<tr>
<td>Glas</td>
<td>chem. components</td>
</tr>
<tr>
<td></td>
<td>analysis of material characteristics, chem.</td>
</tr>
<tr>
<td>Metal</td>
<td>components, molecular structure, elemental</td>
</tr>
<tr>
<td></td>
<td>or isotope components</td>
</tr>
<tr>
<td>Paint, Tinctures</td>
<td>and distribution, texture</td>
</tr>
</tbody>
</table>

## Purpose of Material Dating Techniques

Determine age of artifact or material
Atomic Spectroscopy Techniques include:
- atomic absorption and emission spectroscopy,
- X-ray fluorescence analysis (XRF),
- proton-induced X-ray emission (PIXE).

Nuclear Spectroscopy Methods range from:
- neutron activation techniques,
- nuclear resonance analysis,
- mass separation techniques
- natural decay measurements.
Physics Methods in Material Dating

Dating methods rely on natural radioactivity:

- radio-carbon dating,
- potassium/argon dating,
- uranium/thorium dating,
- analysis of radiation damage,
- thermoluminiscence

critical parameter, time-scale of radioactive clock!
1.2. Basic Principles of Atomic Physics

Extremely simplified quantum mechanical model of the atom is the Bohr model based on Rutherford scattering experiments. Negative electrons are ‘bound’ by electric (Coulomb) attraction to positive nucleus.

The atomic nucleus:
- positive charge: $+1.6 \cdot 10^{-19} \text{ C}$
- atomic mass: $\sim A \cdot 1.66 \cdot 10^{-24} \text{ g}$
- miniscule size: $\sim 5 \cdot 10^{-13} \text{ cm}$

The electron orbits:
- negative charge: $-1.6 \cdot 10^{-19} \text{ C}$
- negligible mass: $\sim 9 \cdot 10^{-28} \text{ g}$
- fair size: $\sim 1-5 \cdot 10^{-10} \text{ cm}$

Only certain orbits for electrons are allowed: quantum states are characterized by certain radius and energy state only limited number of electrons allowed per quantum state.
The Hydrogen Atom

\[ E_n = -\frac{Z^2 E_0}{n^2} \quad E_0 = 13.6 \text{ eV} \]

\( E_0 \) is energy necessary to ionize atom
\( Z \) is charge of nucleus, \( Z = 1 \)

n = main quantum number
\( \ell = n-1 \) orbital momentum quantum number
Mathematics of Quantum Transitions

Hydrogen atom: single proton in nucleus, single electron in orbit

\[ r_n = n^2 \cdot 0.529 \cdot 10^{-9} [m] \]

**Electron orbit radius**

\[ E_n = -\frac{13.606}{n^2} [eV] \]

**Electron orbit energy**

\[ n = 1,2,3,4,\ldots. \]

Electron transition between orbits requires or releases energy:

Energy comes quantized as light particles: photons

\[ 1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J} \]
Transition between energy orbitals

Possible emission or absorption of light with fixed wavelengths by transitions of electrons between orbits! Wavelength depends on energy difference between orbits!

Hydrogen emission spectrum

Balmer Series

$E_n = -\frac{13.6}{n^2}$
Energy and wavelength of emitted or absorbed light photons

\[ E_\nu = E_{n_i} - E_{n_f} = \hbar \cdot c \cdot R_H \cdot \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \]

\[ E_\nu = 13.6 \cdot \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \text{[eV]} \]

\( R_H \equiv \text{Rydberg Constant: } 1.097 \cdot 10^7 \text{ } [m^{-1}] \)

\( \hbar \equiv \text{Planck Constant: } 6.626 \cdot 10^{-34} \text{ } [Js] \)

\( c \equiv \text{Speed of Light: } 2.987 \cdot 10^8 \text{ } [m/s] \)

\[ E_\nu = h \cdot \nu = \frac{\hbar \cdot c}{\lambda} \quad \frac{1}{\lambda} = R_H \cdot \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \]
Examples

Calculate the wavelength of a photon emitted by an electron transition in the hydrogen atom from the \( L \)-shell \((n = 2)\) to the \( K \)-shell \((n = 1)\) (Lyman-series \( L_\alpha \))!

\[
\frac{1}{\lambda} = R_H \cdot \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) = R_H \cdot \left( \frac{1}{1^2} - \frac{1}{2^2} \right) = 1.097 \cdot 10^7 [1/m] \cdot 0.75
\]

\[\lambda = 121.5 \cdot 10^{-9} \text{ m} = 121.5 \text{ nm} : \text{wavelength}\]

In interstellar space you find highly excited hydrogen atoms which emit radio waves. The wavelength corresponds transition from \( n = 273 \) to \( n = 272 \). Calculate the wavelength!

\[
\frac{1}{\lambda} = R_H \cdot \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) = R_H \cdot \left( \frac{1}{272^2} - \frac{1}{273^2} \right) = 1.097 \cdot 10^7 [1/m] \cdot 9.88 \cdot 10^{-8}
\]

\[\lambda = 0.923 \text{ m} : \text{radio wavelength}\]
The wavelength range extends from $10^{-15}$ m ($\gamma$-radiation) or $10^{-9}$ m (X-ray radiation) through $10^{-6}$ m (visible light) to radio wave lengths 1 m.
Each element has its own characteristic transitions depending on the orbit quantum numbers and the charge $Z$ (number of electrons, protons). These transitions can be analyzed by so-called spectroscopy of light to determine the elemental abundance!
Multi-Electron Atoms

More than one electron, Z is the charge and determines the chemical characteristics of the element, e.g. Z=1 (Hydrogen) Z=47 (Silver). Electron transitions and photon emission is more complex and depends on Z and the shielding $S_n$ by inner electron shells.

$$E_n = - (Z - S_n)^2 \cdot \frac{13.6}{n^2} \approx -(Z - 1)^2 \cdot \frac{13.6}{n^2}$$

$$E_K = E_n - E_1 = -(Z - 1)^2 \cdot \frac{13.6}{n^2} + (Z - 1)^2 \cdot \frac{13.6}{1^2}$$

$$E_K = (Z - 1)^2 \cdot 13.6 \cdot \left(1 - \frac{1}{n^2}\right) = \frac{hc}{\lambda_K}$$

$$\lambda_K = \frac{hc}{E_\gamma} = \frac{hc}{E_n - E_1}$$

K-transitions to $n=1$
X-ray transitions in high Z atoms
Example: Calculate the K and L x-ray lines for Ag

\[ E_K = (Z-1)^2 \cdot 13.6 \text{[eV]} \cdot \left(1 - \frac{1}{n_i^2}\right) \]

Ag: \( Z = 47 \)

\[ E_{K\alpha} = 46^2 \cdot 13.6 \text{[eV]} \cdot \left(1 - \frac{1}{4}\right) = 21583 \text{[eV]} \]

\[ E_{K\beta} = 46^2 \cdot 13.6 \text{[eV]} \cdot \left(1 - \frac{1}{9}\right) = 25580 \text{[eV]} \]

\[ E_L = (Z-1)^2 \cdot 13.6 \text{[eV]} \cdot \left(\frac{1}{2^2} - \frac{1}{n_i^2}\right) \]

\[ E_{L\alpha} = (46)^2 \cdot 13.6 \text{[eV]} \cdot \left(\frac{1}{4} - \frac{1}{9}\right) = 3997 \text{[eV]} \]
transition scheme with orbital momentum quantum number

<table>
<thead>
<tr>
<th>( \ell )</th>
<th>( j (\ell \pm 1/2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5/2</td>
</tr>
<tr>
<td>2</td>
<td>3/2</td>
</tr>
<tr>
<td>1</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Level splitting due to elliptic orbitals
higher accuracy x-ray energies

<table>
<thead>
<tr>
<th>Z</th>
<th>Element</th>
<th>Kα₁</th>
<th>Kα₂</th>
<th>Kβ₁</th>
<th>Lα₁</th>
<th>Lα₂</th>
<th>Lβ₁</th>
<th>Lβ₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>Ag</td>
<td>22.163</td>
<td>21.990</td>
<td>24.942</td>
<td>2.984</td>
<td>2.978</td>
<td>3.151</td>
<td>3.348</td>
</tr>
</tbody>
</table>

Easy to obtain:  
http://xray.uu.se/hypertext/XREmission.html  
http://www.csrri.iit.edu/mucal.html  
http://ie.lbl.gov/xray/  

Typical spectra:  
http://ie.lbl.gov/xray/ag.htm
To use atomic spectroscopy methods you need to excite the atoms of the material that you want to analyze. The decay back to the atomic ground state configuration causes the emission of photons with characteristic energies!