L X-ray satellite effects on the determination of photon emission intensities of radionuclides

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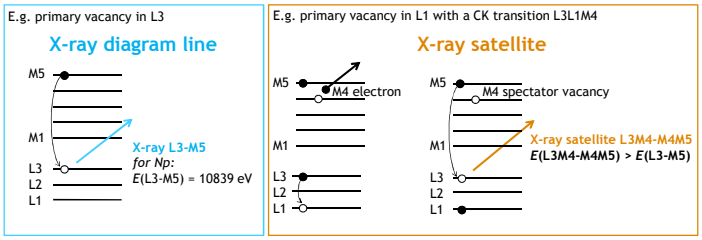
Introduction

Can the presence of X-ray satellites be ignored for L X-ray emission intensity measurements?

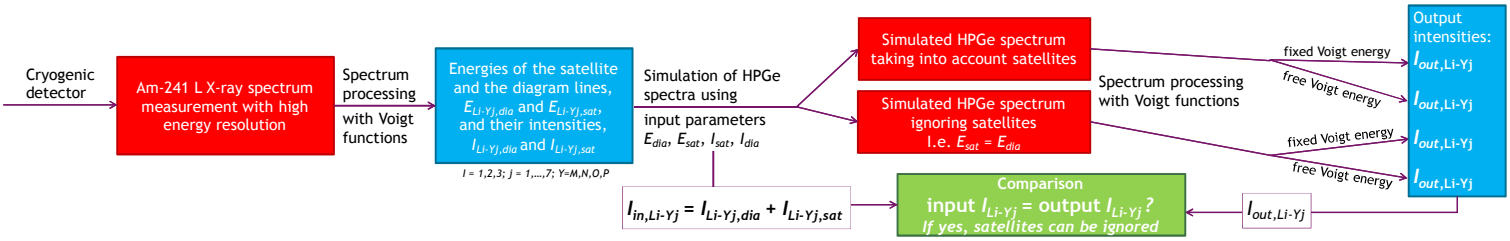
- L X-ray spectra of radionuclides can contain X-ray satellites due to the presence of multiple vacancies created by Coster Kronig (CK) transitions or the shake-off process.
- L X-ray intensities of radionuclides are usually measured with semiconductor spectrometers.
- Based on the assumption that their FWHM energy resolutions are larger than the energy shift of the X-ray satellites, the satellites are ignored during the fitting procedure.

→ Is this assumption valid or does it cause large systematic errors on L X-ray intensity measurements?

What is an X-ray satellite?

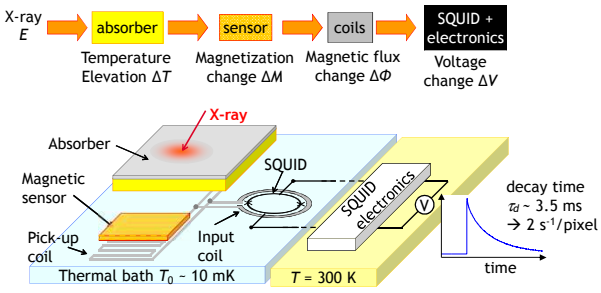


Method



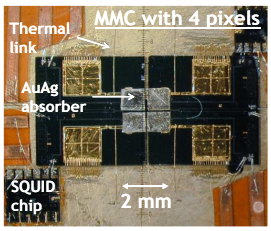
X-ray spectrum of Am-241 using a high energy resolution Metallic Magnetic Calorimeter (MMC)

Physics principle of MMCs

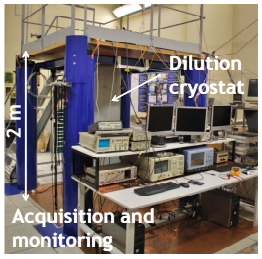


Signal	Noises	Energy resolution
$\Delta V \propto \Delta T = \frac{E}{C(T_0)}$ $\tau_d = \frac{C}{G}$	Statistical fluctuations: $\sigma_{SFN} \propto \sqrt{\varepsilon E}$, $\varepsilon = k_B T_0 < 1\,\mu eV$ Thermodynamic fluctuations: $\sigma_{TFN} \propto \sqrt{T_0^2 \cdot C(T_0)}$ SQUID electronics: $\sigma_{SQUID} \propto \sqrt{T_0}$	High resolution at very low T_0

Experimental set-up



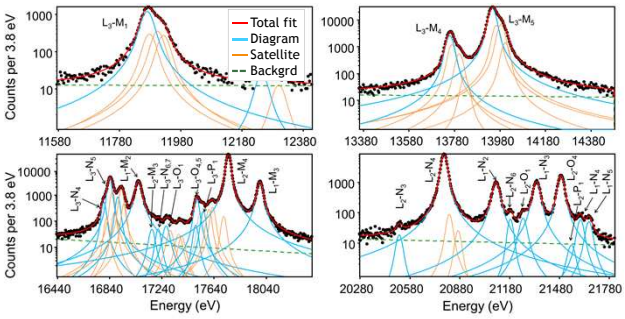
→ Count rate = 10 s⁻¹



L X-ray spectrum of Am-241

- The **FWHM resolution of 26 eV** allows the main satellites to be fitted
- Only L3-Yj X-rays have satellites due to CK transitions L1L3M or L2L3M
- 2-4 Voigt functions are needed to fit L3-Yj transitions
  - → 1 Voigt for the diagram (energy $E_{Li\text{-}Yj,dia}$ and intensity $I_{Li\text{-}Yj,dia}$)
  - → 1-3 Voigt for the satellites ($E_{Li\text{-}Yj,sat}$ and $I_{Li\text{-}Yj,sat}$)

→ $I_{in,Li\text{-}Yj} = I_{Li\text{-}Yj,dia} + I_{Li\text{-}Yj,sat}$

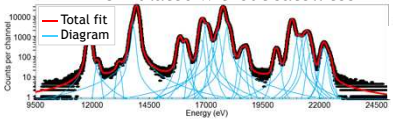


Simulated HPGe spectra and their fitting procedures

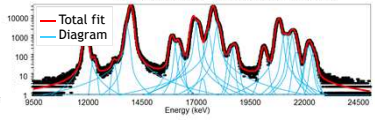
Two L X-ray spectra were simulated with a FWHM energy resolution of a typical HPGe:

- spectrum with satellites, input parameters: $E_{Li\text{-}Yj,sat}$, $E_{Li\text{-}Yj,dia}$, $I_{Li\text{-}Yj,sat}$, $I_{Li\text{-}Yj,dia}$
- spectrum without satellite, input parameters: $E_{Li\text{-}Yj,dia}$, $I_{Li\text{-}Yj,sat}$, $I_{Li\text{-}Yj,dia}$
  - → satellite energy shifts are null: $E_{Li\text{-}Yj,sat} = E_{Li\text{-}Yj,dia}$

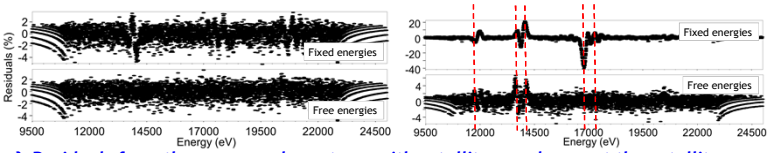
Simulated without satellites



Simulated with satellites



The presence of satellites is ignored during the fitting procedure. For each of these two spectra, processing with fixed or with free Voigt energies is used. The residuals are shown below.



→ **Residuals from the processed spectrum with satellites are larger at the satellite energies.**

Comparison between the input and output intensities ($I_{in,Li\text{-}Yj}$ and $I_{out,Li\text{-}Yj}$) from the fitting procedures using the deviation d: $d = \left(I_{out,Li\text{-}Yj} - I_{in,Li\text{-}Yj}\right) / I_{in,Li\text{-}Yj} \cdot 100$

The 2 spectra are labeled "*wo*" (without satellite), "*w*" (with satellites), and the 2 fitting procedures "*fixed*" (fixed energies), "*free*" (free energies).

X-ray transition	E (eV)	Intensity I_{in} (%)	Without sat. $d_{WO,fixed}$	Without sat. $d_{WO,free}$	With sat. $d_{W,fixed}$	With sat. $d_{W,free}$	X-ray group	Without sat. $d_{WO,fixed}$	Without sat. $d_{WO,free}$	With sat. $d_{W,fixed}$	With sat. $d_{W,free}$
L3-M1	**11871**	**2.36**	**-0.4**	**-0.2**	**-1.2**	**-1.2**	Ll	-0.4	-0.2	-1.2	-1.2
L3-M4	**13759**	**3.31**	**3.8**	**-1.9**	**-26.1**	**11.2**	Lα	0.1	-0.1	-2.1	-0.5
L3-M5	**13945**	**31.31**	**-0.3**	**0.1**	**0.4**	**-1.7**					
L2-M1	15861	0.99	0.6	0.5	0.0	0.7	Lη	0.6	0.5	0.0	0.7
L3-N5	**16841**	**7.00**	**0.7**	**-29.1**	**-0.8**	**-62.1**					
L1-M2	17062	4.25	-0.2	-1.1	27.5	-4.3					
L3-O4	**17509**	**1.65**	**-3.5**	**0.6**	**-12.3**	**-13.7**	Lβ	0.2	0.0	1.1	0.2
L2-M4	**17750**	**30.77**	**-0.2**	**-0.1**	**1.8**	**0.5**					
L1-M3	17992	3.54	1.2	-0.2	1.7	1.4					
L2-N3,4	20785	7.52	0.6	0.8	1.8	1.3					
L1-N2	21102	1.19	2.8	-0.3	3.0	0.4					
L1-N3	21337	1.19	1.8	-4.2	3.6	-5.1	Lγ	0.4	0.5	1.5	0.8
L2-O4	21489	1.61	-5.1	2.2	-2.9	1.4					

- The intensity deviations $d_w > d_{wo}$ for L3-Yj
- $d_w \approx d_{wo}$ for L1-Yj and L2-Yj

→ The satellites introduce systematic errors for individual L X-ray intensities with semiconductor detectors.

$d_w > d_{wo}$, *but* d_w remains relatively small.

→ semiconductor detectors can provide satisfactory results for L X-ray groups.

Conclusion

From a high energy resolution X-ray spectrum of Am-241, we have shown the presence of intense satellites. With the simulation of HPGe spectra with and without satellites, and by applying different fitting procedures, we have demonstrated that the measurement of L X-ray intensities can have significant systematic errors due to the satellites, however these deviations are relatively small for L X-ray group intensities.