PRESPEC-AGATA setup: Optimizing the target positions with Bayesian data analysis*

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Abstract

The target position in spectroscopy experiments such as PreSPEC-AGATA [1] influences the signal-to-noise ratio. Therefore precise information on the position of the target is needed to find low cross-section γ-ray transitions. The optimal positioning of a target is a non-trivial question. This report establishes a unidimensional model allowing a robust determination of the target even with a low signal-to-noise ratio.

The model is probabilistic and allows us to find N Doppler-corrected γ rays while accounting for atomic background. The model assumes the transitions to generate Gaussian spectral features on top of an exponential decay background. We proceed to the fit of the model with the PreSPEC-AGATA nuclear structure experiment *S428*, while naturally folding in measurement uncertainties. Within the Bayesian analysis framework, we are able to optimize the width of the γ-ray transitions and characterize related uncertainties as a function of the position of the target.

For this particular experiment, we find that the optimal position is shifted by -1 mm along the horizontal axis (x) and -4 mm along the vertical axis (y) with respect to the measured position. We demonstrate the power of our model and analysis method, that is applicable to the calibration of other experiments.

Introduction

In the PreSPEC-AGATA experiments [1], we measure the target position at the beginning of the experiment. This measurement is subject to uncertainties. To refine the position measurement and reduce uncertainties, we use the sensitivity of the AGATA array [2] to Doppler correct the two K-α X-rays of the uranium beam emitted in flight at half the speed of light. Specifically, the Doppler correction requires knowledge of the emission angle of the X-rays. Therefore we need to measure the position of the interacting uranium ion on the target, and the position of the X-rays detected in AGATA. The comparison of the pulse shape inside an AGATA crystal with a data-base provides the interaction position of the X-rays in the detector [2]. In this present work, we neglect variations due to the AGATA detectors and we focus on the target positioning uncertainties only.

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Minimization technique

Generation of a mesh of offsets We suppose that the (x, y) position [1] of the target might be shifted with respect to the measured position. In order to consider all realistic target positions, we generate a mesh of offsets in the (x, y) plane. We set the mesh resolution to 1 mm, which corresponds to the resolution achieved to determine the ion position on the target. At each position offset of the mesh, we Doppler correct the X-rays with their re-calculated angle of emissions.

Model the data at each point of the mesh In order to determine precisely the width of the transitions, we need to model our data at each point of the mesh with a model that includes the two X-ray transitions, the background radiations, and the measurement uncertainties. We consider our model $M(\vec{E},\vec{\Pi})$ as parametric function of $\vec{E}$ a set of energies, and $\vec{\Pi}$ a set of parameters.

Definition of the Likelihood The determination of the parameters of our model that reproduce our data requires the definition of similarity. In a Bayesian approach, we can define this similarity as a Likelihood function $p(Data(\vec{E})|Model(\vec{E},\vec{\Pi}))$. It quantifies the similarity between our $Data$ and the $Model$ given a set of parameters $\vec{\Pi}$. The law of large numbers allows us to approximate the observed number of counts N_{obs} at given energy E by a Gaussian distribution. Thus, we define our Likelihood function as:

$$p(N_{obs}(\vec{E})\,|\,N_{pred}(\vec{E},\vec{\Pi})) = \frac{1}{\sqrt{2\pi N_{pred}(\vec{E},\vec{\Pi})}} \exp\left(-\frac{1}{2}\frac{(N_{obs}(\vec{E})-N_{pred}(\vec{E},\vec{\Pi}))^2}{N_{pred}(\vec{E},\vec{\Pi})}\right),$$

where $N_{pred}(\vec{E},\vec{\Pi})$ is the predicted number of counts by the model at an energy E.

Determination of the model parameter For each parameter of our model, we provide an *a-priori* range of variation, that defines our parameter space. In order to constrain our two X-rays transition, we add a condition on the energy difference between the first and second X-ray transition.

The parameter space needs to be explored in order to find the set of parameters $\vec{\Pi}$ that maximizes the Likelihood

[1]The (x, y) plane is perpendicular to the beam axis.

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probability. The exploration needs to converge quickly to the absolute maximum of Likelihood and to avoid local maxima. Therefore, we explore the parameter space with a Monte-Carlo Markov-Chain algorithm called *emcee* [5].

Establishment of the model

The model takes into account the two X-ray transitions of uranium at 94.6 and 98.4 keV.Their energy separation is close to the limit of resolution that can be achieved under Doppler broadening effect [4]. In addition, the beam induces a substantial background and we observed an unknown transition at energy of ∼115 keV, that both need to be modelled properly too. The blue curve in Fig. 1 corresponds to the data.

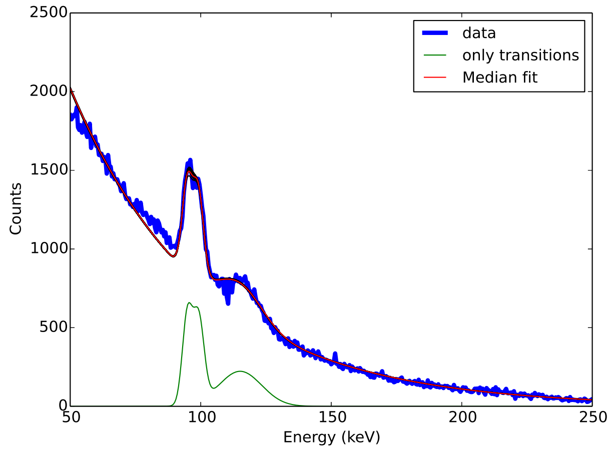

Figure 1: Doppler corrected histogram of the uranium X-ray transitions is plotted in the figure together with the fit. The blue curve is the observed dataset, while the red line indicates our "best-fit" model. The green curve shows only the transition components of our model.

Transitions model We first assume that each of the N transitions generates a Gaussian line in the energy spectrum. Thus, we have three parameters to describe the i-th line: the count amplitude A_i, the mean energy μ_i, and the energy variance σ_i^2. The i-th transition can be described by:

$$g_i(E; A_i, \mu_i, \sigma_i) = \frac{A_i}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(E-\mu_i)^2}{2\sigma_i^2}\right).$$

Background continuum The background in our case represents a source of noise to find our transitions in the spectra. This noise is mostly induced by the beam. We model this component with a unique exponential decay function:

$$noise(E) = A \cdot \lambda \exp\left(-\lambda E\right),$$

with an amplitude A and the decay parameter λ.

Mixture model Once we have defined the transition features and the noise, we can combine the different components as the sum of all transitions on top of the continuum:

$$M(E; \Pi) = \sum_{i=1}^{n} g_i(E; E_i, \sigma_i, A_i) + noise(E; A, \lambda),$$

where $\vec{\Pi}$ is the vector of all the parameters:
$\vec{\Pi} = \{(E_i, \sigma_i, A_i)\}_{i\in[1..n]} + (A, \lambda)\}$.

Result on the optimum target position

We used a Monte-Carlo Markov-Chain (MCMC) method to optimize our model, and in particular, we used a specific implementation: *emcee* [5]. With this method, we determine at each point of the mesh, the optimum set of parameters $\vec{\Pi}$ and therefore optimum width of the two X-ray transitions. The plot of the width of the transition as a function of the offset in both x and y direction is shown in Fig. 2.

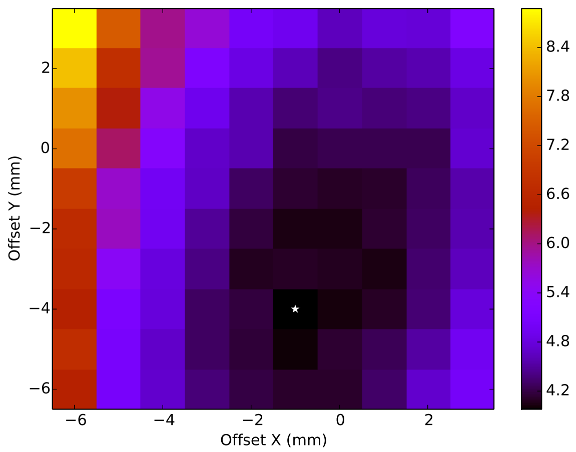

Figure 2: Each (x, y) bins corresponds to an offset applied to the measured target position. We weight each bins by the product of the two X-ray median widths. The white star highlights the minimum obtained in an offset $(x, y) = (-1, -4)$ mm. The X-Ray median widths are indicated by the color bar on the right-hand side.

The product of the transition width is minimum at a position offset of $(x, y) = (-1, -4)\ mm$. The curve in red in Fig. 1 corresponds to our model evaluated for the median value of our set of parameters $\vec{\Pi}$, with the optimum target offset.

Conclusion

The model we describe in this paper, along with the introduction of a Bayesian data analysis techniques allows us to determine the optimum target position for the PreSPEC-AGATA experiment. This newly determined position improves the energy resolution obtained after Doppler correction. Indeed the width of the transition of the 94.6 keV

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X-ray transition pass from $\sigma = 1.99^{+10}_{-9}$ keV for the measured target position to $\sigma = 1.92^{+9}_{-8}$ keV after the target shift [2].

The thick target (700 mg/cm^2 beryllium) implies a large velocity spread, and therefore a substantial Doppler broadening. It becomes necessary to include the latter into the model. Moreover, we will consider the angle of emission of the X-rays to further increase the precision and accuracy of the calibration.

References

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[2]The error on the width values are given at the percentile of 16, and 84.

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