Advanced analytic methods for neutron spectra unfolding and pulse shape discrimination

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Motivation and Introduction

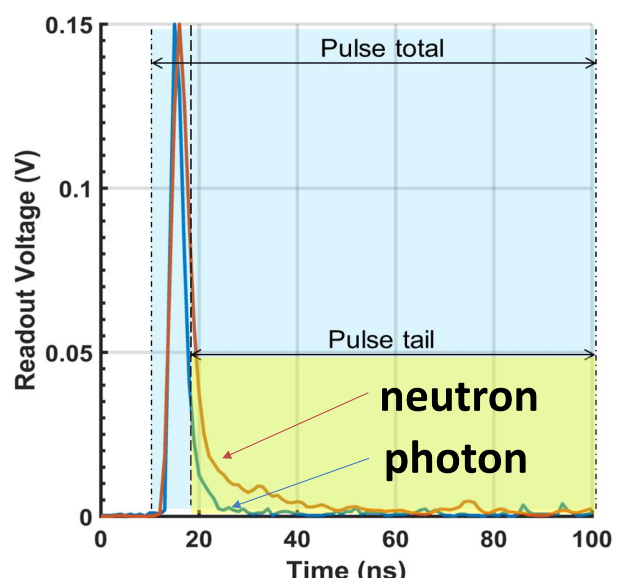
- **Neutron spectrometry without time-of-flight** can be extremely useful in safeguards and nonproliferation applications, e.g. neutron imaging for material accountancy and verification (Fig. 1), to discriminate between fissile material and other neutron emitting sources.
- **Organic scintillators are intrinsically able to reconstruct the incident neutron spectrum, by unfolding the measured pulse-height distribution with the known response of the scintillator to monoenergetic neutrons.**
- The use of organic scintillators is well established for the measurement of neutron spectra above several hundred keV.
- Pulse-height spectrum results from energy deposited both by proton recoils, produced by neutron interactions with H-1 nuclei in the scintillator, and electron recoils, generated by gamma-rays via Compton scattering.
- **Improved algorithms are needed both to maximize gamma-neutron discrimination capability and increase fidelity of neutron spectrometry and thus decrease the neutron energy detection threshold.**

Fig. 1 Radiation Inspection System [1].

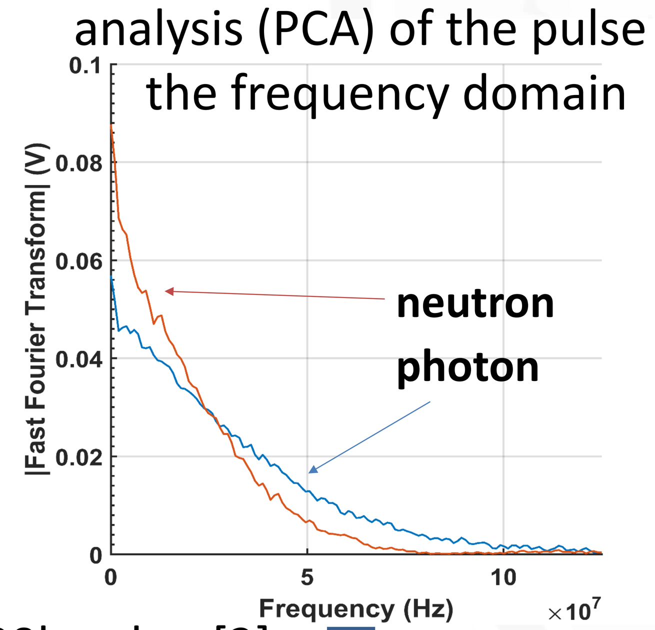
Pulse shape discrimination

GAMMA-NEUTRON DISCRIMINATION

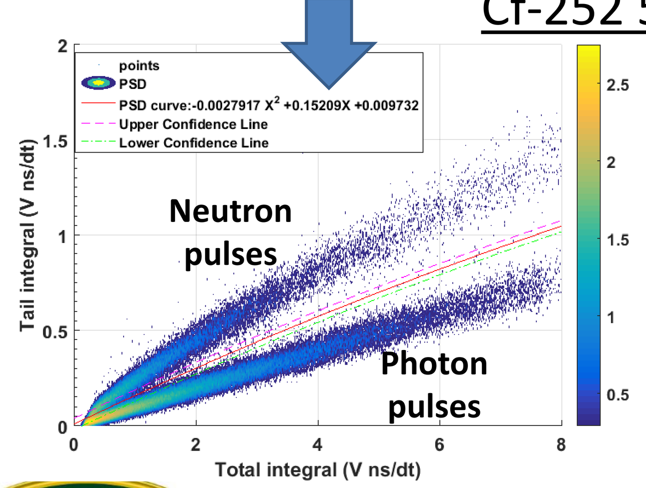
Charge Integration (CI) of the pulse in the time domain

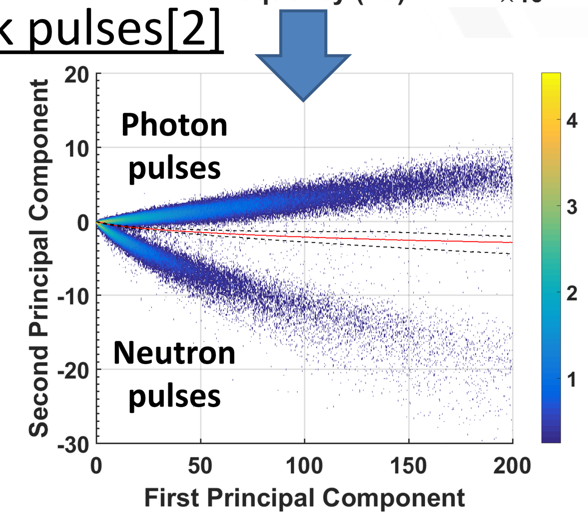


Principal component analysis (PCA) of the pulse in the frequency domain



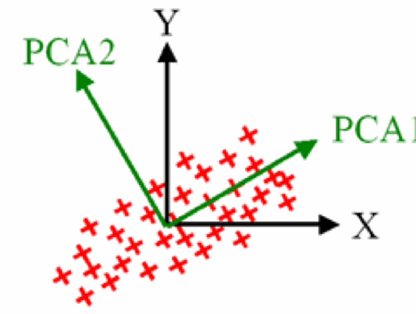
Cf-252 500k pulses[2]



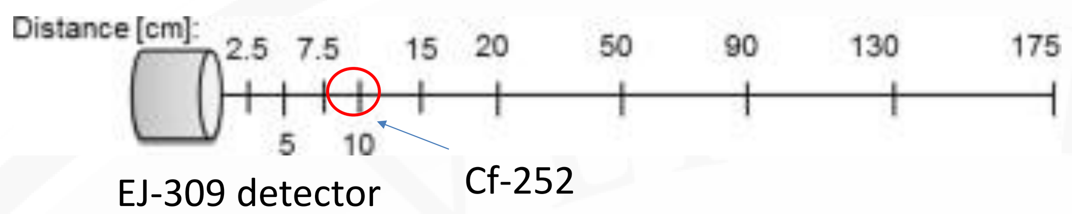


More efficient data representation:

- 2 or 3 dimensions sufficient (out of more than 100)
- Powerful to classify millions of pulses



Two methods tested and compared using experimental data [2]



Experimental setup

- Cf-252 @ 10 cm from the detector face, total count rate ~ 900 cps
- **Cs-137 moved from 2.5 cm to 175 cm SDD**

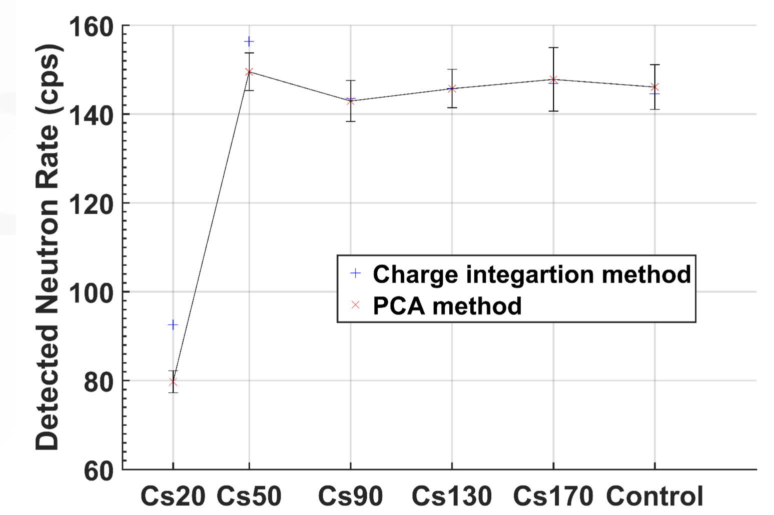


Fig. 2 Neutron count rate classified using the CI and PCA methods.

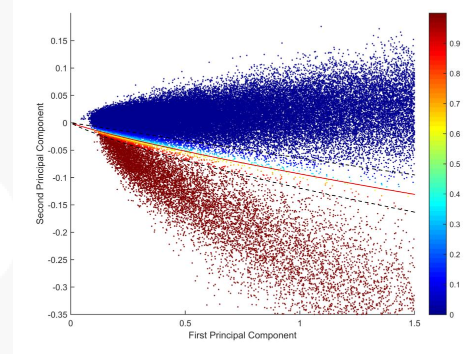


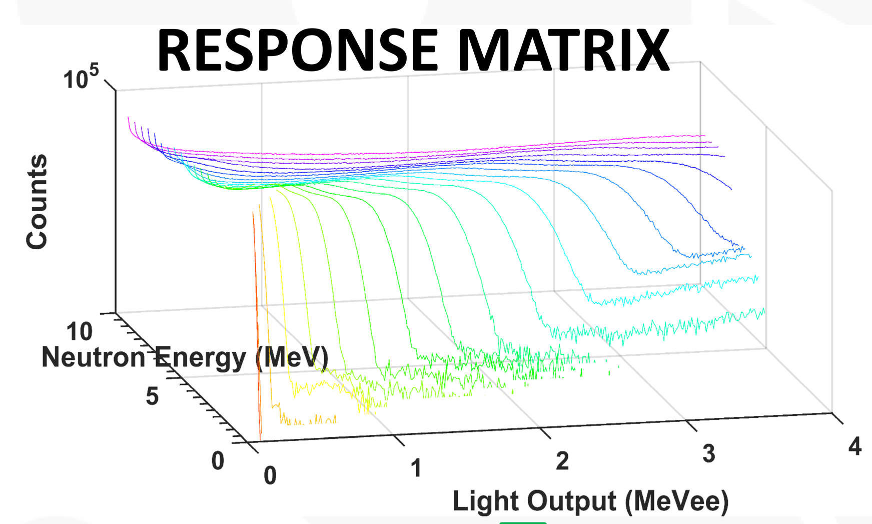
Fig 3. Posterior probability of each pulse to result from a neutron detection.

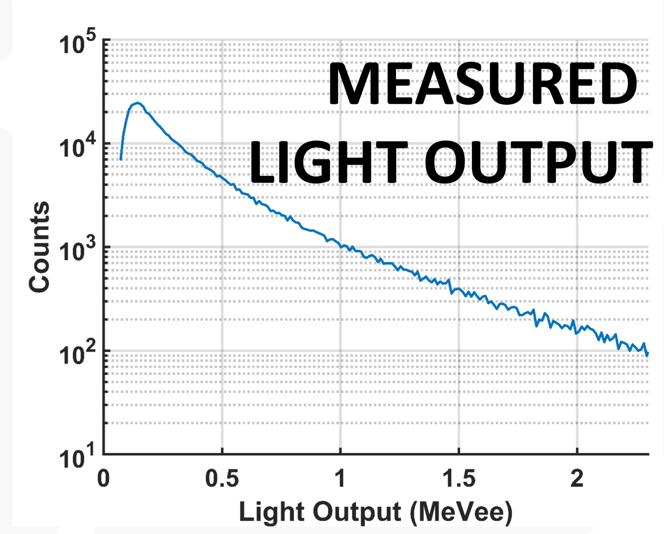
Neutron spectra unfolding

UNFOLDING

$$z_{0i} + e_i = \sum_j R_{ij} \Phi_j \quad (i = 1 \dots M)$$

z_{0i} light output spectrum
M is the number of detection channels
$R_i(E)$ is the detector response
$\Phi(E)$ Neutron spectrum flux cm^{-2}





UNFOLDING ALGORITHM

Approach A (new!!!):
Poisson unfolding, for discrete events
- **Convex optimization technique**: SPIRAL [4]
- **Markov chain Monte Carlo** : automatic adjustment of the regularization parameters + a posteriori measures of uncertainty

Approach B:
MAXED [2] solves a regularized weighted least squares problem incorporating prior information

NEUTRON SPECTRUM

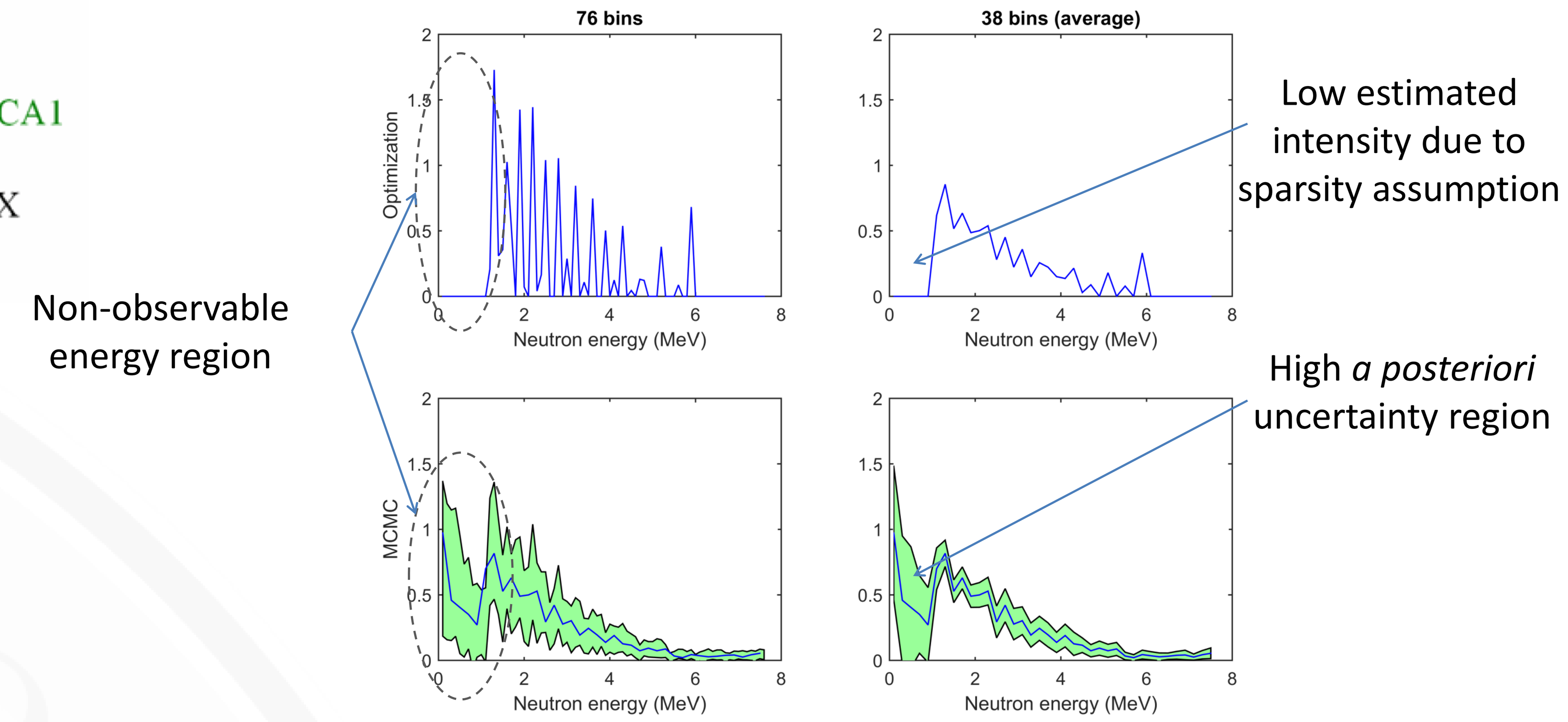


Fig. 4: Cf-252 neutron energy spectra unfolded by SPIRAL [1] (top) and the proposed MCMC method (bottom)

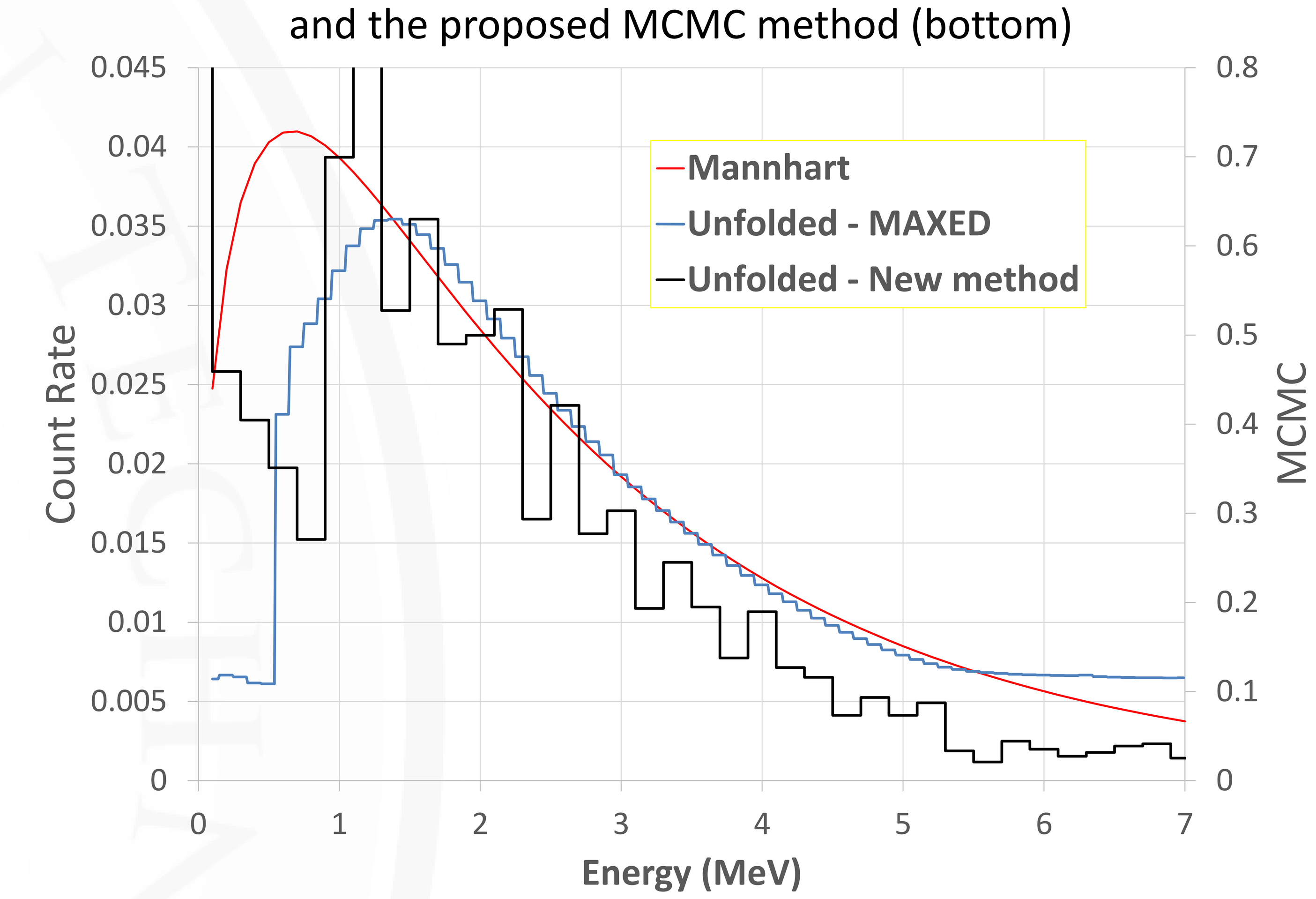


Fig. 5. Unfolded neutron energy spectrum from Cf-252 detected with an EJ-309 liquid scintillator; the Watt spectrum from Mannhart is shown for reference.

Conclusions and Future Work

PCA

- Principal component analysis does not require parameter optimization to perform the classification.
- Domain transformation mitigates the effect of temporal delays.

Unfolding

- Novel unfolding algorithm to be used for neutron energy reconstruction using a single liquid scintillator (ill-conditioned response matrix).
- Trend of the reconstructed neutron spectrum compares well with analytic spectrum function → uncertainty compensation needed.

Incorporate the pulse shape discrimination to the unfolding algorithm to improve fidelity at low energies.

References
[1] “Technology R&D for Arms Control”, Office of Nonproliferation Research and Engineering, Spring 2001.
[2] A. C. Kaplan, et al., “EJ-309 pulse shape discrimination performance with a high gamma-ray-to-neutron ratio and low threshold,” Nucl. Instr. Meth. A, **729**, (2013)
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[4] Harmany, Z. T. et al., “This is SPIRAL-TAP: Sparse Poisson Intensity Reconstruction Algorithms—Theory and Practice”, IEEE Trans. Image Process., 2012

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