

# ePSproc: Post-processing suite for ePolyScat electron-molecule scattering calculations

Paul Hockett<sup>1</sup>

<sup>1</sup>National Research Council of Canada

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## *Article details*

Software metaper, structured for the [Journal of Open Research Software \(JORS\)](#).

Online version (Authorea) can be found at [https://www.authorea.com/users/71114/articles/122402/\\_show\\_-article](https://www.authorea.com/users/71114/articles/122402/_show_-article)

Github (software repository): [github.com/phockett/ePSproc](https://github.com/phockett/ePSproc)

Figshare repository (manuscript & source files): DOI: [10.6084/m9.figshare.3545639](https://doi.org/10.6084/m9.figshare.3545639)

10/08/16 - This fork for review.

12/11/16 - [arXiv version uploaded, 1611.04043](#)

03/09/19 - Finally working on a python version, see [Github pages](#) for updates. Full documentation now on [Read the Docs](#).

## (1) Overview

# ePSproc: Post-processing suite for ePolyScat electron-molecule scattering calculations

## Paper Authors

1. Hockett, Paul ([femtolab.ca](https://femtolab.ca))

## Paper Author Roles and Affiliations

1. National Research Council of Canada, 100 Sussex Drive, Ottawa, Ontario, Canada

## Abstract

ePSproc provides codes for post-processing results from ePolyScat (ePS), a suite of codes for the calculation of quantum scattering problems, developed and released by Lucchese & co-workers (Gianturco et al., 1994; Natalense and Lucchese, 1999; R. R. Lucchese and Gianturco, 2016). ePS is a powerful computational engine for solving scattering problems, but its inherent complexity, combined with additional post-processing requirements, ranging from simple visualizations to more complex processing involving further calculations based on ePS outputs, present a significant barrier to use for most researchers. ePSproc aims to lower this barrier by providing a range of functions for reading, processing and plotting outputs from ePS. Since ePS calculations are currently finding multiple applications in AMO physics (see below), ePSproc is expected to have significant reuse potential in the community, both as a basic tool-set for researchers beginning to use ePS, and as a more advanced post-processing suite for those already using ePS. ePSproc is currently written for Matlab/Octave, and distributed via Github: <https://github.com/phockett/ePSproc>.

## Keywords

1. Photoionization
2. Photoelectron angular distributions
3. Electron-molecule scattering
4. ePolyScat
5. AMO physics
6. Quantum physics
7. Dipole matrix elements
8. Matlab
9. Octave

## Introduction

The **ePolyScat (ePS) suite**, developed and released by Lucchese & co-workers (Gianturco et al., 1994; Natalense and Lucchese, 1999; R. R. Lucchese and Gianturco, 2016), provides an open source software tool to the AMO physics community for the calculation of a range of quantum scattering problems. At heart, the codes use a Schwinger variational method to solve the continuum electron wavefunction, for a given scattering potential and continuum energy. ePS is written in Fortran 90, and makes use of MPI for parallel processing. The code is modular, with an input file consisting of a range of commands to define the specific calculation(s) of interest, and typically produces a monolithic output file, consistent with the traditional style of quantum chemistry software (e.g. Gamess, Gaussian etc.). Some additional processing tools, and supplementary output file options, are available to the user. User interaction is at the command line or via text files.

**ePSproc, a suite of codes for post-processing of ePS outputs**, aims to provide existing, or potential, ePS users with tools for:

- Parsing of ePS output files and extraction of segments/data of interest.
- Visualization of ePS calculation results.
- Additional post-processing, based on the raw matrix elements.

The workflow for ePolyScat and ePSproc is illustrated in figure 1, and the full range of the current functionality of ePSproc is given in table 1, including some future aims. Full details of each function can be found in the [source code and documentation](#).

ePSproc evolved from the use of ePS for a variety of calculations, in particular for molecular and laboratory frame photoelectron angular distributions, and high-harmonic generation (Wörner et al., 2010; Bertrand et al., 2012); these works were, in turn, typically based on prior publications from ePS contributors developing the underlying computational methods, e.g. (Toffoli et al., 2007; Le et al., 2009). In all cases, ePS was utilized to calculate dipole matrix elements for a specific problem, and significant post-processing was required to produce the desired results. These various computations resulted in a range of Matlab scripts and functions, for both basic and advanced processing of ePS outputs. In this context “basic” functionality consists of visualization of ePS results, and post-processing of the output data in a manner similar to other tools within the ePS suite (e.g. basic frame transformations), while “advanced” functionality consists of making use of the raw matrix elements in further computations (e.g. laboratory frame angular distributions for aligned molecular ensembles (Hockett, 2015), Wigner time-delays (Hockett et al., 2016; Hockett, 2016)). Aspects of these various existing, and carefully tested, codes have now been consolidated into ePSproc.

The first release of ePSproc (v1.0.0) is aimed at photoionization problems. In this release, ePS output files are parsed, and the user can then plot photoionization cross-sections and molecular frame photoelectron angular distributions (MFPADs). The former are taken directly from the ePS output, while the latter incorporates processing of the dipole matrix elements output by ePS for calculation of the molecular frame photoelectron scattering distributions for any arbitrary light polarization and molecular frame alignment, as specified by the user. The formalism employed is detailed in the following section.

Future releases of ePSproc will include calculations for a wider range of cases, including time-dependent aligned distributions and high-harmonic generation. A port of the software to the Python language, for a true open-source implementation, is also planned.

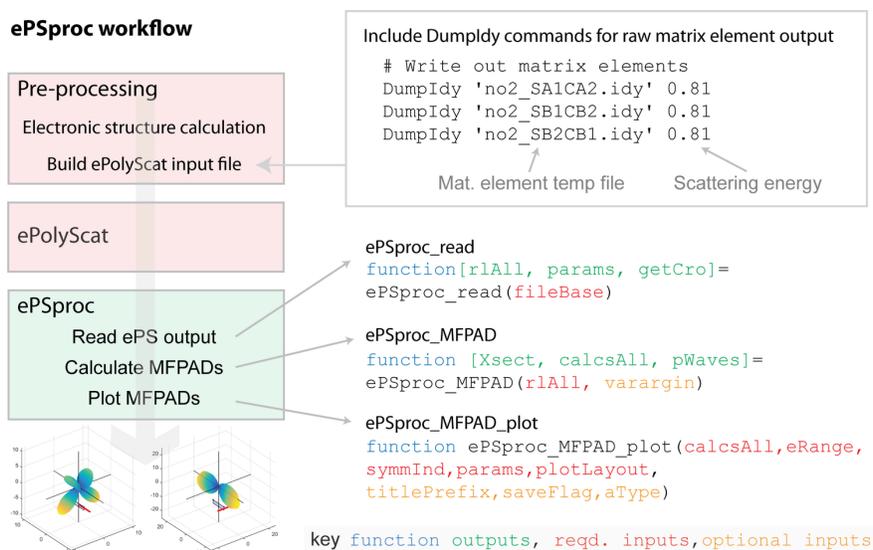


Figure 1: Overview of workflow for ePolyScat and ePSproc to calculate MFPADs. For export of raw matrix elements into ePS output file, the **DumpIdy** command is required in the input file for each set of records. The ePSproc function prototypes are shown in detail, further details of each function can be found at the heads of the [source codes](#).

Function	Implemented	Details
ePSproc_read	Y	Read information from main ePS output file. Reads details of molecular geometry, scattering energies, cross-sections (GetCros segments) and raw matrix elements (DumpIdy segments).
ePSproc_MFPAD	Y	Calculate MFPADs for all input sets of matrix elements, for a given polarization state and geometry (Toffoli et al., 2007).
ePSproc_MFPAD_plot	Y	Plot results from ePSproc_MFPAD.
ePSproc_NO2_MFPADs_demo	Y	Basic script for running the example/benchmark calculations.
ePSproc_LFPAD	N	Similar to ePSproc_MFPAD, but for LFPADs.
ePSproc_AFPAD	N	Calculate aligned frame (AF) PADs for a given molecular axis distribution (Hockett, 2015).
ePSproc_HHG	N	Calculate recombination matrix elements for use in HHG calculations (Le et al., 2009).
ePSproc_wignerT	N	Calculate ionization (Wigner) time-delays (Hockett et al., 2016).

Table 1: List of main functions in ePSproc, implementation status in the [initial release v1.0.0](#), and the purpose of the function. For full details, see the [source code](#) and descriptions within. The references listed provide examples of each usage case, including the relevant theoretical formalism.

## Formalism

Molecular frame photoelectron angular distributions (MFPADs) can be defined as per eqns. 1-3 of ref. (Toffoli et al., 2007):

$$I_{\mu_0}^{p_i, p_f}(\theta_{\hat{k}}, \phi_{\hat{k}}, \theta_{\hat{n}}, \phi_{\hat{n}}) = \frac{4\pi^2 E}{c g_{p_i}} \sum_{\mu_i, \mu_f} |T_{\mu_0}^{p_i, \mu_i, p_f, \mu_f}(\theta_{\hat{k}}, \phi_{\hat{k}}, \theta_{\hat{n}}, \phi_{\hat{n}})|^2 \quad (1)$$

$$T_{\mu_0}^{p_i, \mu_i, p_f, \mu_f}(\theta_{\hat{k}}, \phi_{\hat{k}}, \theta_{\hat{n}}, \phi_{\hat{n}}) = \sum_{l, m, \mu} I_{l, m, \mu}^{p_i, \mu_i, p_f, \mu_f}(E) Y_{lm}^*(\theta_{\hat{k}}, \phi_{\hat{k}}) D_{\mu, -\mu_0}^1(R_{\hat{n}}) \quad (2)$$

$$I_{l, m, \mu}^{p_i, \mu_i, p_f, \mu_f}(E) = \langle \Psi_i^{p_i, \mu_i} | \hat{d}_{\mu} | \Psi_f^{p_f, \mu_f} \varphi_{klm}^{(-)} \rangle \quad (3)$$

In this formalism:

- $I_{l, m, \mu}^{p_i, \mu_i, p_f, \mu_f}(E)$  is the radial part of the dipole matrix element, determined from the initial ( $i$ ) and final ( $f$ ) state electronic wavefunctions  $\Psi_i^{p_i, \mu_i}$  and  $\Psi_f^{p_f, \mu_f}$ , photoelectron wavefunction  $\varphi_{klm}^{(-)}$  and dipole operator  $\hat{d}_{\mu}$ . The wavefunctions are indexed by irreducible representation (i.e. symmetry) by the labels  $p_i$  and  $p_f$ , with components  $\mu_i$  and  $\mu_f$  respectively;  $l, m$  are angular momentum components,  $\mu$  is the projection of the polarization into the MF (from a value  $\mu_0$  in the LF). Each choice of energy and irreducible representation (and components thereof) corresponds to a single scattering calculation in ePolyScat, and produces a set of matrix elements  $I_{l, m, \mu}^{(c)}$ , where ( $c$ ) denotes that the results correspond to a single scattering calculation, and the matrix elements are again expanded in the spherical basis quantum numbers  $l, m, \mu$ . These are the raw matrix elements which ePSproc works with.
- $T_{\mu_0}^{p_i, \mu_i, p_f, \mu_f}(\theta_{\hat{k}}, \phi_{\hat{k}}, \theta_{\hat{n}}, \phi_{\hat{n}})$  is the full matrix element (expanded in polar coordinates) in the MF, where  $\hat{k}$  denotes the direction of the photoelectron  $\mathbf{k}$ -vector, and  $\hat{n}$  the direction of the polarization vector  $\mathbf{n}$  of the ionizing light. Note that the summation over components  $\{l, m, \mu\}$  is coherent, and hence phase sensitive.
- $Y_{lm}^*(\theta_{\hat{k}}, \phi_{\hat{k}})$  is a spherical harmonic.

- $D_{\mu, -\mu_0}^1(R_{\hat{n}})$  is a Wigner rotation matrix element, with a set of Euler angles  $R_{\hat{n}} = (\phi_{\hat{n}}, \theta_{\hat{n}}, \chi_{\hat{n}})$ , which rotates/projects the polarization into the MF .
- $I_{\mu_0}(\theta_{\hat{k}}, \phi_{\hat{k}}, \theta_{\hat{n}}, \phi_{\hat{n}})$  is the final (observable) MFPAD, for a polarization  $\mu_0$  and summed over all symmetry components of the initial and final states,  $\mu_i$  and  $\mu_f$ . Note that this sum can be expressed as an incoherent summation, since these components are (by definition) orthogonal.
- $g_{p_i}$  is the degeneracy of the state  $p_i$ .

The laboratory frame photoelectron angular distribution (LFPAD) for a single molecular orientation can be similarly defined:

$$T_{\mu_0}^{p_i \mu_i, p_f \mu_f}(\theta_{\hat{k}}, \phi_{\hat{k}}, \theta_{\hat{n}}, \phi_{\hat{n}}) = \sum_{l, m, \mu} I_{l, m, \mu}^{p_i \mu_i, p_f \mu_f}(E) Y_{lm}^*(\theta_{\hat{k}}, \phi_{\hat{k}}) D_{\mu, \mu_0}^1(R_{\hat{n}}) D_{m, m_0}^l(R_{\hat{n}}) \quad (4)$$

Which is similar to eqn. 2, except with an additional rotation matrix element to rotate the spherical harmonics into the LF (defined by the polarization vector of the incident radiation), with components  $m_0$ .

As defined above, ePSproc works from the raw matrix elements, defined in sets corresponding to a single scattering calculation output from ePolyScat,  $I_{l, m, \mu}^{(c)}$ . Application of the equations above, defined in terms of operations on each set of matrix elements and summation over sets, allows computation of the MF and LFPADs for any desired polarization geometry. Similar formalisms can be applied to obtain related quantities, such as recombination matrix elements for high harmonic generation, or Wigner ionization time-delays.

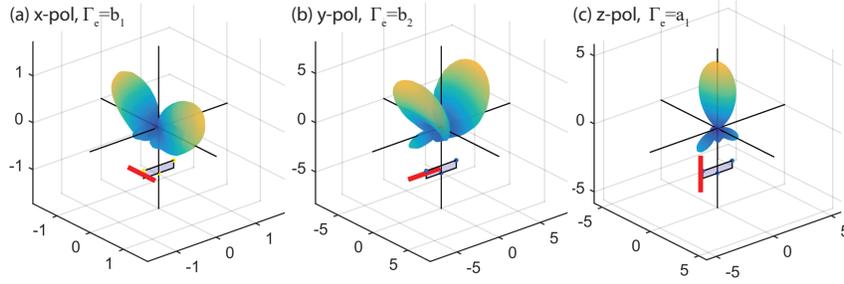


Figure 2: Example output from ePSproc. MFPADs for ionization of  $NO_2$ , via removal of a  $(4a_1)$  electron at 22 eV (resulting in electron energies of 0.7eV), leading to the  $(4a_1)^{-13}A_1$  state of  $NO_2^+$  (c.f. figure 5 of ref. (Toffoli et al., 2007)). Each panel shows the results for a single ePS calculation (set of matrix elements  $I_{l, m, \mu}^{(c)}$ ) corresponding to a different polarization geometry. The polarization geometries are denoted as  $x$ ,  $y$  and  $z$ , corresponding to continuum symmetries  $\Gamma_e = b_1, b_2, a_1$  respectively. Units are the angle-resolved cross-sections in MB.

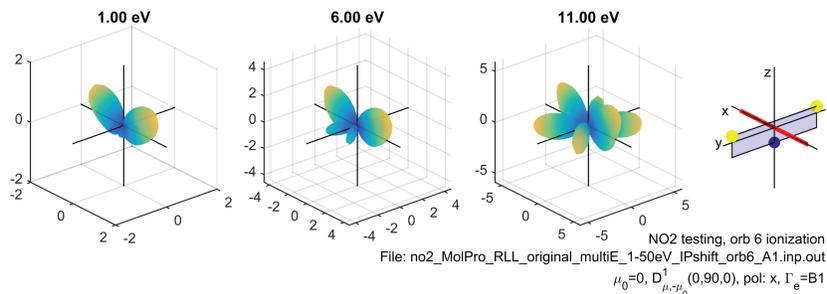


Figure 3: Example output from ePSproc. MFPADs for ionization of  $NO_2$ , via removal of a  $(4a_1)$  electron, leading to the  $(4a_1)^{-13}A_1$  state of  $NO_2^+$  (as per figure 2), for different continuum energies. The molecular structure and polarization geometry ( $x$ ) is shown in the last panel. The text, as output by `ePSproc-MFPAD_plot()`, includes a user-supplied description `titlePrefix` (line 1), the source filename (line 2) and the (user-defined) calculation parameters for the E-field polarization in the LF  $\mu_0$ , frame rotation LF $\rightarrow$ MF (defined by Euler angles  $R_{\hat{n}} = (\phi_{\hat{n}}, \theta_{\hat{n}}, \chi_{\hat{n}})$ ) and continuum symmetry  $\Gamma_e$ . Units are the angle-resolved cross-sections in MB.

## Quality control

As well as the existing scientific publications listed above, which indicate the lineage of the current suite, the release version of ePSproc has been carefully tested for the generation of MFPADs against benchmark calculations provided by R.R. Lucchese (one of the original ePS authors, as described above), based on calculations originally published in ref. (Toffoli et al., 2007). An overview of the testing and results is provided in figure 4.

For the testing procedure, input matrix elements for ePSproc were obtained from an ePS calculation (version E3), running under Ubuntu LTS 14. The electronic structure inputs for this calculation were the sample  $NO_2$  Gaussian output, provided with the ePS.E3 release (R. R. Lucchese and Gianturco, 2016), although a new ePS input file (including matrix element output via `DumpIdy` commands) was created for this computation (see figure 1 for visualization of this workflow). Benchmark results, provided by R.R. Lucchese, originated from the output of the ePS `OrientCro` routine (which provides a data-file of angle-resolved cross-sections, expanded as harmonics, for a given polarization state), and were post-processed using Matlab code also provided by R.R. Lucchese. The resulting  $(\theta, \phi)$  gridded data was then plotted (figure 4(b)). The reprocessing was verified against the previously published results, figure 4(a).

The new calculations, with post-processing in ePSproc, are shown in figure 4(c), and were directly compared to the (reprocessed) benchmark results via numerical subtraction; the results of this comparison are shown in figure 4(d), indicating agreement with the benchmark calculations to  $10^{-9}$ . In this case, the comparison is very good, although it is of note that this testing does not differentiate between differences in the raw ePS outputs (which could arise for many reasons, both computational and due to differences in the input files) and differences in the post-processing.

The ePSproc results shown were obtained on an 64-bit Intel Core I7 system, running Matlab R2010b under Ubuntu LTS release 14, and similar verification has been successfully obtained using a 64-bit Intel Core I5 system, running Matlab R2015a under Windows 7. (The results have not been verified with Octave at the current time.)

The current release of ePSproc includes the required ePS output file and demo script to reproduce the benchmark post-processing, and should be the first test run by a new user (users running ePS can, additionally, test the ePS portion of the benchmark calculations, via changes to the ePS input file). The demo calculation also provides the opportunity for the user to further test ePSproc post-processing and visualization by, for

instance, testing alternative polarization geometries. Additional details are provided in the documentation accompanying ePSproc.

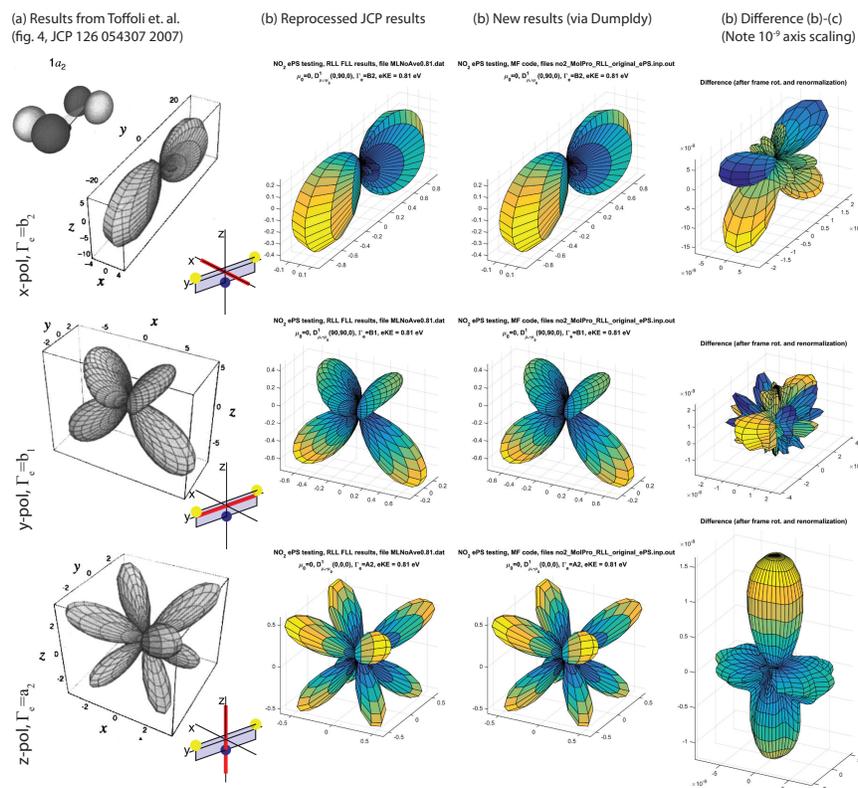


Figure 4: ePSproc benchmarking. Comparison between (a) previously published ePS results (reproduced from fig. 4 of ref. (Toffoli et al., 2007)), for ionization of  $NO_2$  at 14.4 eV, and ejection of a ( $1a_2$ ) electron - the ionizing orbital is shown top left; (b) reprocessed MFPADs from the original data, output by ePolyScat's OrientCro function (original results provided by R.R. Lucchese); (c) comparison results using ePSproc; (d) difference between results (b) and (c), note the  $10^{-9}$  scaling, indicating excellent agreement. Each row shows the results for a different polarization geometry,  $x$ ,  $y$  and  $z$ , corresponding to continuum symmetries  $\Gamma_e = b_2, b_1, a_2$  respectively. See main text for further details.

## (2) Availability

### Operating system

Any OS capable of running Matlab or Octave. File parsing currently makes use of Windows or Linux command-line tools for searches, so may require small modification for other operating systems.

## Programming language

The code suite is written for Matlab/Octave. No Matlab proprietary or toolbox functions are used in ePSProc, so any version of Matlab or Octave should be suitable. The current version has been tested in Matlab releases R2010b, R2013a, R2015a.

## Additional system requirements

None.

## Dependencies

None - no additional libraries required.

## List of contributors

- P. Hockett - development of ePSProc.
- R. R. Lucchese, N. Sanna, A. P. P. Natalense, and F. A. Gianturco - development and release of ePS ([Gianturco et al., 1994](#); [Natalense and Lucchese, 1999](#); [R. R. Lucchese and Gianturco, 2016](#)).

Special thanks to R.R. Lucchese, for general help with ePS usage and providing benchmark ePS outputs and post-processed MFPADs for verification of ePSproc outputs.

## Software location:

### Archive

**Name:** Figshare

**Persistent identifier:** DOI: [10.6084/m9.figshare.3545639](https://doi.org/10.6084/m9.figshare.3545639)

**Licence:** CC-BY

**Publisher:** P. Hockett

**Version published:** Initial release, v1.0.0

**Date published:** Release 17/04/16, archived 07/08/16

### Code repository

**Name:** GitHub

**Persistent identifier:** <https://github.com/phockett/ePSproc>

**Licence:** GNU GPL

**Date published:** 17th April 2016 (v1.0)

## Language

English

### (3) Reuse potential

As detailed above, the use of ePS has recently become widespread, with users in a range of related areas of AMO physics. It is anticipated that many of these users would find a use for ePSproc. Potential new users will, hopefully, find that the bar to entry for ePS is lowered since, at a basic level, ePSproc provides an easy, and well-tested, methodology for bringing raw matrix elements from ePS into Matlab. This provides a rapid and transparent means of analyzing and visualizing ePS results, and removes the requirement for researchers to develop and test their own post-processing techniques. Beyond this, there are a range of potential usage cases, from the basic exploration of MFPADs in order to build physical intuition, to more detailed and extensive computations considering, e.g. molecular dynamics, aligned ensembles, HHG, etc. (see table 1 for some examples). In release 1.0.0 of ePSproc only MFPAD calculations are implemented, and additional usage cases will be incorporated in future releases. The applications listed in table 1 have already been developed, but still require code rationalization and integration into ePSproc before release. It is anticipated that users will also develop post-processing routines for other usage cases, making use of the low-level ePS I/O and computational functions implemented in ePSproc, and these additions could be incorporated into future releases to further extend the capabilities of the code.

Additional future plans to extend ePSproc include the creation of a library of sample calculations (initially based on the publications cited above), and porting the code to a fully open-source framework, probably the python language.

User support for ePSproc can be obtained directly from the author, via the [project GitHub page](#) or by email.

### Acknowledgements

PH thanks the multiple collaborators and co-authors - many of whom are listed in the references - who encouraged and suggested the cavalier use of ePS "out of the box", for many different problems incorporating electron scattering and photoionization. This spirit of "shoot first, ask questions later" indeed raised many questions which, eventually, necessitated proper use of ePS and careful post-processing of the results, and sharpened related foundational expertise - efforts well worth making.

### Competing interests

The authors declare that they have no competing interests.

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