

s t d 2

A Program Package for computing excited states
and response functions via simplified TD-DFT
methods (sTDA, sTD-DFT, SF-sTD-DFT,
XsTDA, XsTD-DFT, and SF-XsTD-DFT)

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User Manual

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General Features and Requirements

- Extremely fast excited state and response calculations with sTDA, sTD-DFT, XsTDA, and XsTD-DFT methods,
- Ground state Kohn-Sham determinant from a hybrid DFT calculation is required or from a range-separated hybrid (RSH) calculation (the procedure is different for sTD or XsTD methods, see below),
- Molden file serves as input (e.g. from TURBOMOLE, MOLPRO, TERACHEM),
 - `g2molden` tool available to interface with GAUSSIAN (see Sec. 5),
 - `qc2molden.sh` script available to interface with Q-CHEM (see Sec. 6),
- Ultrafast excited states in combination with extended tight-binding ground state procedure (sTDA-xTB and sTD-DFT-xTB only),
- Linear and quadratic responses to compute dynamic (hyper)polarizabilities, two-photon absorption cross-sections, and excited-state absorption spectra in an ultra-fast way,
- Spin-flip versions (SF-sTD-DFT and SF-XsTD-DFT[only hybrid functionals]),
- Natural transition orbitals and the RespA approach^[21] to interpret response properties, including natural response orbitals.

1 About the Program

The std2 program is the rebranded and updated version of the stda program. Originally, stda was implemented only for the simplified time-dependent density functional theory using the Tamm-Dancoff approximation (sTDA) method^[1]. With the implementation of more simplified quantum chemistry (sQC) methods in stda, the name was not fitting the application of the program anymore. The std2 program can compute excited states and response properties with the simplified time-dependent density functional theory (sTD-DFT)^[2], sTDA^[1], eXact integral sTD-DFT (XsTD-DFT)^[3,4], and the XsTDA^[3,4] methods. Originally, it was developed as an add-on for the TURBOMOLE suite of programs^[5,6].

Since version 1.2, the program uses a Molden^[7] input file that contains the Cartesian GTO basis as well as the molecular orbital coefficients. Molden files generated by TURBOMOLE, MOLPRO^[8] and TERACHEM^[9] can be processed. GAUSSIAN^[10] can be used via the interfacing tool `g2molden` (see Sec. 5) and Q-CHEM^[11] via `qc2molden.sh` (see Sec. 6). We are interested in making the program compatible with different quantum chemistry program packages and are open for suggestions. However, in the present version the std2 code can work with Cartesian GTO basis functions only and the quantum chemistry software must provide Cartesian basis functions. Spectra may be computed

with the SpecDis^[12,13] program¹. Alternatively, the provided plotting tool (`g_spec`, see below) may be used.

Since version 1.5, A+B/2-corrected^[14] dipole velocity rotatory strengths are computed by default in sTDA calculations. Large parts of the code make use of OpenMP parallelization and the Intel MKL, thus setting the environmental variables `OMP_NUM_THREADS` and `MKL_NUM_THREADS` to the number of available CPUs may accelerate the calculations. With version 1.6, the `std2` program is able to compute linear and quadratic response functions^[15] to evaluate dynamic (hyper)polarizabilities and excited-state absorption spectra^[16].

Since version 1.6.1, a spin-flip version of the sTD-DFT (SF-sTD-DFT) method is implemented^[17] as well as the natural transition orbital analysis^[18].

With version 1.6.2, molecular optical rotations can be computed at the sTD-DFT level^[19] and the whole linear and quadratic responses deck was speeded-up.

In version 1.6.3, we are able to compute two-photon absorption cross-sections^[20], to interpret molecular response properties using the RespA approach^[21], and a dual-threshold scheme is also available to treat efficiently very large systems with a central chromophore^[22].

With version 2.0.0, a major update happened with the availability of both XsTD-DFT and XsTDA methods that no longer use semi-empirical integrals. The `std2` program is also interfaced natively with the `libcint` integral library^[23] to compute one- and two-electron integrals. Range-separated hybrid functionals are also available natively with XsTD-DFT and XsTDA schemes.

In the following, a short outline of the theory will be given followed by a documentation on the program.

2 Theoretical background

To compute excited states via `std2` (Sec. 2.1) or sTD-DFT (Sec. 2.2), a ground state Kohn-Sham (or Hartree-Fock) calculation needs to be carried out with one of the programs mentioned above. The orbitals obtained from this calculation are then used in the sTDA/sTD-DFT procedure. Instead of a Kohn-Sham reference, the orbitals may be obtained via the semi-empirical extended tight-binding (xTB) scheme (see Sec. 7).

2.1 Simplified Tamm-Dancoff approximation to TD-DFT

The time-dependent density functional theory (TD-DFT) response problem can be expressed as the following non-Hermitian eigenvalue problem^[24].

$$\begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^* & \mathbf{A}^* \end{pmatrix} \begin{pmatrix} \mathbf{X} \\ \mathbf{Y} \end{pmatrix} = \begin{pmatrix} \omega & 0 \\ 0 & -\omega \end{pmatrix} \begin{pmatrix} \mathbf{X} \\ \mathbf{Y} \end{pmatrix} \quad (1)$$

In the Tamm-Dancoff approximation (TDA), the matrix \mathbf{B} is neglected^[25] which leads to:

¹We thank Dr. Torsten Bruhn for the interfacing.

$$\mathbf{A}\mathbf{X}_{TDA} = \omega_{TDA}\mathbf{X}_{TDA} \quad (2)$$

Three simplifications then yield the simplified Tamm-Dancoff approach (sTDA)^[1]:

1. Neglect the response of exchange-correlation functional
2. Evaluate the two-electron integrals as damped Coulomb interactions between transition/charge density monopoles
3. Restrict the configuration space to a user-specified energy range of excitations

In the following notation, the indices ijk refer to occupied, abc to virtual orbitals and pq to general orbitals (either occupied or virtual). The elements of the simplified matrix \mathbf{A}' are then given as:

$$A'_{ia,jb} = \delta_{ij}\delta_{ab}(\epsilon_a - \epsilon_i) + \sum_{A,B}^{N_{atoms}} (s_k q_{ia}^A \gamma_{AB}^K q_{jb}^B - q_{ij}^A \gamma_{AB}^J q_{ab}^B) \quad (3)$$

q_{pq}^A and q_{pq}^B are the transition/charge density monopoles located on atom A and B , respectively. These are obtained from Löwdin population analysis^[26]. ϵ_p is the Kohn-Sham orbital energy of orbital p . In the spin-restricted case, $s_k = 2$ for singlet-singlet and $s_k = 0$ for singlet-triplet excitations. γ_{AB}^K and γ_{AB}^J are the Mataga-Nishimoto-Ohno-Klopman damped Coulomb operators for exchange-type (K) and Coulomb-type (J) integrals, respectively^[27,28,29].

$$\gamma_{AB}^J = \left(\frac{1}{(R_{AB})^\beta + (a_x \eta)^{-\beta}} \right)^{\frac{1}{\beta}} \quad (4)$$

$$\gamma_{AB}^K = \left(\frac{1}{(R_{AB})^\alpha + \eta^{-\alpha}} \right)^{\frac{1}{\alpha}} \quad (5)$$

Here, η is the arithmetic mean of the chemical hardness of atom A and B . α and β are the global fit parameters of the method and are dependent on the amount of non-local Fock exchange a_x in the functional (see Ref. 1 for more details).

The matrix \mathbf{A}' includes all excitations up to a user-specified energy threshold (see Sec. 3). In order not to miss important configurations beyond this threshold, such configurations will be selected perturbatively:

$$E_{thr}^{(2)} \stackrel{!}{<} \sum_{ia} \frac{|A'_{ia,kc}|^2}{A'_{kc,kc} - A'_{ia,ia}} \quad (6)$$

For each excited configuration kc , the summed coupling to all excited configurations ia is evaluated (according to Eq. 6). The configuration kc refers to an excitation of an electron from the occupied orbital k to the virtual orbital c with a diagonal element

$A'_{kc,kc}$ larger than the energy threshold. On the other hand, the configurations ia have diagonal elements $A'_{ia,ia}$ smaller than the threshold and are therefore included in the matrix \mathbf{A}' from the very beginning.

If the summed coupling of configuration kc with all configurations ia is larger than $E_{thr}^{(2)}$, the configuration kc will be included (default: $E_{thr}^{(2)} = 10^{-4} E_h$).

2.2 Simplified Time-Dependent-Density Functional Theory

In the same simplified manner, the full TD-DFT problem (Eq. 1) can be solved^[2]. The elements of the simplified matrix \mathbf{B}' are given as:

$$B'_{ia,jb} = \sum_{A,B}^{N_{atoms}} (s_k q_{ia}^A \gamma_{AB}^K q_{bj}^B - a_x q_{ib}^A \gamma_{AB}^K q_{aj}^B) \quad (7)$$

a_x is the amount of non-local Fock exchange in the density functional (e.g. 0.2 for B3LYP). This approach has proven to yield more reliable transition moments and therefore better UV/VIS and ECD spectra than sTDA (see Ref. 2 for more information).

The α and β parameters (see Eqs. 4 and 5) are identical in sTDA and sTD-DFT. Thus, γ_{AB}^J and γ_{AB}^K are the same in both approaches. The same is true for the dimension of the matrices \mathbf{A}' and \mathbf{B}' , i.e. the same configuration selection as in sTDA is performed.

2.3 Simplified Linear and Quadratic Response Theory

The linear-response matrix equation is similar to equation 1 when the perturbation is turned on by taking its first derivative with respect to the external applied electric field ($\frac{\partial}{\partial \vec{F}_\zeta} |_{\vec{F}=0}$):

$$\left[\begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{A} \end{pmatrix} - \omega \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \right] \begin{pmatrix} \mathbf{X}_\zeta(\omega) \\ \mathbf{Y}_\zeta(\omega) \end{pmatrix} = - \begin{pmatrix} \mu_\zeta \\ \mu_\zeta \end{pmatrix}, \quad (8)$$

where the derivative of the first-order perturbation of the density matrix defines the frequency-dependent response vectors $\frac{\partial D_{ai}^{(1)}(\omega)}{\partial \vec{F}_\zeta} |_{\vec{F}=0} = X_{\zeta,ai}(\omega) + Y_{\zeta,ai}(\omega)$ and where $\mu_{\zeta,ai} = \langle \phi_a | \hat{\mu}_\zeta | \phi_i \rangle$. In the sTD-DFT framework, the linear-response vectors^[15] used to compute the polarizability and the first hyperpolarizability are obtained by solving equation 8:

$$[(\mathbf{A}' + \mathbf{B}') - \omega^2(\mathbf{A}' - \mathbf{B}')] (\mathbf{X}'_\zeta(\omega) + \mathbf{Y}'_\zeta(\omega)) = -2\mu_\zeta. \quad (9)$$

The polarizability is then determined by

$$\alpha'_{\zeta\eta}(-\omega; \omega) = -2 \sum_{ai} \mu_{\zeta,ai} (X'_{\eta,ai}(\omega) + Y'_{\eta,ai}(\omega)), \quad (10)$$

and the second-harmonic generation first hyperpolarizability in the sTD-DFT approximations reads

$$\beta'_{\xi\zeta\eta}(-2\omega; \omega, \omega) = A' - B', \quad (11)$$

$$A' = \sum_{perm.\xi,\zeta,\eta} \left\{ \sum_{aij} X'_{\xi,ai}(-2\omega) [-\mu_{\zeta,ij}] Y'_{\eta,aj}(\omega) \right\}, \quad (12)$$

$$B' = \sum_{perm.\xi,\zeta,\eta} \left\{ \sum_{iab} X'_{\xi,ai}(-2\omega) [-\mu_{\zeta,ab}] Y'_{\eta,bi}(\omega) \right\}, \quad (13)$$

where linear response vectors are determined for ω and -2ω . Two-photon absorption cross-sections are obtained by the single residue of the first hyperpolarizability and the state-to-state unrelaxed dipole moments by the double residue.

2.4 Simplified Spin-Flip TD-DFT

In the spin-flip formalism, only single excitations from the α space to the β space are considered. For collinear functionals, exclusively the $(i_\alpha j_\alpha | a_\beta b_\beta)$ two-electron integrals remain and the SF-sTD-DFT^[17] eigenvalue equation becomes:

$$\mathbf{A}'^{\alpha \rightarrow \beta} \mathbf{X}^{\text{SF}} = \omega \mathbf{X}^{\text{SF}}, \quad (14)$$

were

$$A'_{i_\alpha a_\beta, j_\alpha b_\beta}^{\alpha \rightarrow \beta} = \delta_{i_\alpha j_\alpha} \delta_{a_\beta b_\beta} (\epsilon_{a_\beta} - \epsilon_{i_\alpha}) - (i_\alpha j_\alpha | a_\beta b_\beta)'_{\alpha \rightarrow \beta}. \quad (15)$$

For simplified spin-flip two-electron integrals, the damped Coulomb operator takes the form:

$$\Gamma_{AB}^{\alpha \rightarrow \beta} = \left(\frac{1}{(R_{AB})^{y_{\alpha \rightarrow \beta}} + (1.4 \times a_x \eta)^{-y_{\alpha \rightarrow \beta}}} \right)^{\frac{1}{y_{\alpha \rightarrow \beta}}}, \quad (16)$$

where

$$y_{\alpha \rightarrow \beta} = a_x + 0.3. \quad (17)$$

From the sTD-DFT state-to-state transition dipole moment expression^[16], its spin-flip analogue reads

$$\langle m | \mu_\xi - \langle 0 | \mu_\xi | 0 \rangle | n \rangle_{SF} = \frac{\sqrt{2}}{2} \left\{ \sum_{a_\beta i_\alpha j_\alpha} \left[X_{i_\alpha a_\beta}^n \mu_{i_\alpha j_\alpha, \xi} X_{j_\alpha a_\beta}^m \right] - \sum_{a_\beta b_\beta i_\alpha} \left[X_{i_\alpha a_\beta}^n \mu_{a_\beta b_\beta, \xi} X_{b_\beta i_\alpha}^m \right] \right\}. \quad (18)$$

Additionally, a spin-flip version of the tight-binding sTD-DFT-xTB method^[14] has been implemented. Here, the effective Fock exchange parameter in the sTDA part is changed to $a_x = 0.36$, whereas $y_{\alpha \rightarrow \beta} = 3.0$. For clarity, it is noted that the monopole correction Δ_K for the “exchange-type” (Coulomb response) integrals is zero in SF-sTD-DFT-xTB. The vTB and xTB parts remain unchanged compared to the original formulation for open shell systems.^[14]

2.5 The eXact Integral Simplified TD-DFT

The XsTD-DFT and XsTDA^[3,4] calculations can start either from a hybrid or RSH ground state calculation. To solve Casida's equation 1, **A** and **B** supermatrices are no longer evaluated using semi-empirical integrals. Instead, the two-electron integrals necessary to evaluate **A** and **B** supermatrice elements are obtained as

$$(ia|jb) \approx \sum_{\alpha\beta} Q_{\alpha}^{ia} Q_{\beta}^{jb} (\alpha\alpha|\beta\beta), \quad (19)$$

where Q_{α}^{ia} transition charges are collected from Löwdin-orthogonalized coefficients $C_{\alpha i}^{low}$ for each basis function α as

$$Q_{\alpha}^{ia} = \sum_{\alpha} C_{\alpha i}^{low*} C_{\alpha a}^{low}, \quad (20)$$

and $(\alpha\alpha|\beta\beta)$ are AOs two-electron integrals in the Mulliken notation. Considering RSH functionals, long-range two electron integrals are also needed:

$$(ia|\text{erf}(\omega r_{12})|jb) \approx \sum_{\alpha\beta} Q_{\alpha}^{ia} Q_{\beta}^{jb} (\alpha\alpha|\text{erf}(\omega r_{12})|\beta\beta). \quad (21)$$

to compute the following matrix elements:

$$A_{ia,jb} = \delta_{ij}\delta_{ab}(\epsilon_a - \epsilon_i) + 2(ia|jb)' - a_x(ij|ab)' - \beta_x(ij|\text{erf}(\omega r_{12})|ab)', \quad (22)$$

and

$$B_{ia,jb} = 2(ia|bj)' - a_x(ib|aj)' - \beta_x(ib|\text{erf}(\omega r_{12})|aj)'. \quad (23)$$

3 Program Options

3.1 Mandatory Input Features

`-f <molden.input>`

Chooses a Molden input file that provides the GTO and MO data. In the case of TURBOMOLE, this file is created by the conversion tool `tm2molden`. Since there is no unique way to specify the GTO and MO data (i.e. the format depends on the program which generates the input), an input check is performed. Molden files generated from TURBOMOLE, MOLPRO, TERACHEM, GAUSSIAN (via `g2molden`, see below) or Q-CHEM (via `qc2molden.sh`, see below) can be processed.

Before starting an actual calculation, it is important to check whether the program correctly reads in your Molden file. Do this by excuting it as:

`std2 -f <molden.input> -chk`

This will perform a check of input read in (by means of a Mulliken population analysis) and print out the `-sty` flag to be used in the actual calculation. By default,

`-sty 1` is used which is compatible with TURBOMOLE. From our experience the flag `-sty 2` works for MOLPRO inputs, while `-sty 3` works for both TERACHEM, GAUSSIAN (via `g2molden`, see below) or Q-CHEM (via `qc2molden.sh`, see below) input files. After you ran the check, you can run the actual calculation by running the program without the `-chk` flag, but using the respective `-sty` flag as well as the options presented below.

`-ax <amount of Fock exchange>`

Specifies the amount of Fock exchange in the density functional (e.g. `-ax 0.25` for PBE0).

`-e <Ethr>`

This specifies the energy threshold (in eV) for configurations to be considered in sTDA or sTD-DFT or SF-sTD-DFT or XsTDA or XsTD-DFT procedures. Important configurations beyond the threshold are selected by perturbation theory and added to the configuration space (see Ref. 1 for details). The default value is 7 eV and it is recommended to adjust this threshold depending on the energy range of interest.

3.2 Optional Features

`-libcintOFF`

Since version 2.0.0, std2 uses the libcint integral library^[23] to compute one- and two-electron integrals. This keyword can trigger the use of the old integral library. This option is not available for XsTD methods.

`-XsTD`

To trigger the use of XsTD methods instead of sTD ones considering global hybrid functionals. Note that XsTD schemes are not available using an xTB ground state. Note also that for XsTDA calculations, the velocity correction is deactivated by default but can be triggered using the `-Bvel` keyword.

`-p <Pthr>`

Defines the selection criterion used to select important configurations beyond the energy threshold `<Ethr>`. E.g. a an input of `-p 5` corresponds to $E_{thr}^{(2)} = 10^{-5} E_h$ (see Eq. 6).

`-lpt <PTmax>`

For very large systems, it might be useful to restrict the space that is scanned to select important configurations. The flag above specifies the energy threshold (in eV) for configurations to be considered. Obviously, it must always be larger than `<Ethr>`. By default, all excitations are considered, but this may be adjusted to e.g., `<PTmax> = 3 · <Ethr>` in case it is necessary.

`-al <alpha> -be <beta>`

This provides user-defined parameters for α and β which are used in the calculation of γ_{AB}^K and γ_{AB}^J , respectively. By default, they are calculated from the amount of Fock exchange and the standard parameters for global hybrid functionals^[1]. It is wise to change these parameters for range-separated hybrid functionals with sTD methods. Parameters for five widely available range-separated hybrid functionals can be found in Ref. 30 (see also Sec. 3.3.2) for sTD methods.

`-t`

Calculate singlet-triplet excitations (using a spin-restricted ground state).

`-rpa`

This invokes the (X)sTD-DFT procedure instead of the default (X)sTDA^[2].

It is possible to get the eigenvectors printed out (in TURBOMOLE format). This is achieved by:

`-vectm <#vec>`

Depending on the method ((X)sTDA or (X)sTD-DFT), this creates the files `ciss.a`, `cist.a`, `sing.a` or `trip.a` and prints out the lowest eigenvectors up to `<#vec>` (i.e., `-vectm 5` will print out the five lowest eigenvectors). If no number is specified, all eigenvectors that were determined are printed, but one should keep in mind that this can lead to very huge files!

`-xtb`

Invoke sTDA-xTB or sTD-DFT-xTB calculation schemes (see Sec. 7). In this case, the `xtb4stda` binary wavefunction file (`wfn.xtb`) is read instead of a Molden input file. The respective parameters α , β , and a_x are set automatically.

`-oldtda`

In the case of sTDA calculations (i.e., `-rpa` is NOT set), this keyword requests to compute the dipole velocity rotatory strengths from `std2` in the “traditional” fashion,

i.e., simply from the \mathbf{X}_{TDA} eigenvector. Since version 1.5, by default the A+B/2 corrected vector is used instead (for details, see Ref.^[14]), which allows to reliably compute electronic circular dichroism spectra even for systems that are otherwise problematic for Tamm-Dancoff approximated methods^[31].

-resp <#wav>

To compute sTD-DFT frequency-dependent polarizabilities and second-harmonic generation first hyperpolarizabilities, you need a file called wavelength in your directory with desired wavelengths. Specify the number of wavelengths after the **-resp** argument. The **-resp** argument implies the **-rpa** argument. Use a slightly larger energy window than for excited states (above 10 eV, 15 eV seems doing great).

-aresp <#wav>

The same as the previous argument but to compute sTD-DFT frequency-dependent polarizabilities only.

-oprot

To compute sTD-DFT frequency-dependent molecular optical rotation in the length formalism. Use **-oprot 1** to use the velocity representation. By default, it will compute the response at the Sodium D-line (589.3 nm) but you may include a file called “wavelength” instead in your directory with desired wavelengths. The program will read the number of lines in the “wavelength” file to know the number of wavelengths to be used for the evaluation of the optical rotation.

-2PA <#states>

To compute sTD-DFT two-photon absorption cross-sections, just specify the number of states you want after the **-2PA** argument. Note that the number of states specified needs to be below or equal to the number of states computed at the sTD-DFT level for a given energy threshold. When doing a two-photon absorption calculation, only two-photon absorption cross-sections are computed. Linear properties are not available due to a change of normalization of excitation and deexcitation vectors. To compute oscillator or rotatory strengths, one should run std2 without the **-2PA <#states>** option.

-s2s <#state>

To compute an excited-state absorption spectrum using unrelaxed state-to-state transition dipole moments, use the **-s2s** argument followed by the reference state number.

-sf

To use the SF-(X)sTD-DFT method^[17] with a high-spin reference. First-SF-state-to-SF-state transitions are computed as well. Use the **-spin** option to get $\langle S^2 \rangle$ of spin-flip states.

-nto <#state>

To compute natural transition orbitals for the **#state** first states. All NTOs are computed in molden files where the orbital energy parameter is in fact the weight of this pair of NTOs. A jmol.spt script file may be used with jmol to generate all NTOs pictures. Then, one can easily visualize them by opening the NTOs.html file.

With this option, doing a polarizability or an optical rotation calculation, it is possible to use the RespA approach^[21] to compute natural response orbitals as well as chemical fragment responses for convenient elucidation of structure–(optical)property relationships. In this case, the number of states does not need to be specified. To compute chemical fragment responses, a file called "fragments" needs to be specified and its content is:

line 1: Number of fragments
line 2: Number of atoms in fragment #1
line 3: Atom identification numbers in fragment #1
line 4: Number of atoms in fragment #2
line 5: Atom identification numbers in fragment #2
...

If this file is not present, only natural response orbitals are computed.

-rw

Saving some memory by writing on the disk large temporary files when running a restricted calculation.

-dual

To use the dual threshold method^[22] for restricted calculations (implying the **-rw** option). With this option, two energy thresholds are used: one for the inner shell specified by the **-e <Ethr>** option and one for the outer shell specified in a file called "dual":

line 1: Energy threshold for the outer shell
line 2: Number of atoms in the inner shell
line 3: Atom ID #1 in the inner shell
line 3: Atom ID #2 in the inner shell
...

`-CAMB3LYP`

To invoke the CAM-B3LYP RSH functional for XsTD schemes only. This keyword implies the `-XsTD` one and all other parameters.

`-wB97XD2`

To invoke the wB97X-D2 RSH functional for XsTD schemes only. This keyword implies the `-XsTD` one and all other parameters.

`-wB97XD3`

To invoke the wB97X-D3 RSH functional for XsTD schemes only. This keyword implies the `-XsTD` one and all other parameters.

`-wB97MV`

To invoke the wB97MV RSH functional for XsTD schemes only. This keyword implies the `-XsTD` one and all other parameters.

`-SRC2R1`

To invoke the SRC2R1 RSH functional for XsTD schemes only. This keyword implies the `-XsTD` one and all other parameters.

`-SRC2R2`

To invoke the SRC2R2 RSH functional for XsTD schemes only. This keyword implies the `-XsTD` one and all other parameters.

3.3 Exemplary Procedure

3.3.1 Using a global hybrid functional

Perform a Kohn-Sham DFT ground state calculation with a hybrid density functional. In this example, we assume a PBE0 calculation was performed with TURBOMOLE. Then run

```
tm2molden
```

and make sure that the GTO/MO data is written into the Molden input file (here: `pbe0.molden.inp`). Let us assume that we are interested in all excitations up to 6 eV. The `std2` program is called by:

```
std2 -f pbe0.molden.inp -ax 0.25 -e 6 > output
```

We pipe the standard output into the file `output`. The program also writes the file `tda.dat` which contains for each state the transition energy and the length and velocity representations of the oscillator and rotatory strengths (in 10^{40} erg · cm³), respectively. To run the same calculation but at the XsTDA level of theory:

```
std2 -f pbe0.molden.inp -ax 0.25 -e 6 -XsTD > output
```

3.3.2 Using a range-separated hybrid functional with sTDA and sTD-DFT schemes

If we have Molden input file from e.g. an ω B97X single-point calculation (here: `wb97x.molden.inp`), the respective sTDA calculation can be performed as:

```
std2 -f wb97x.molden.inp -ax 0.56 -be 8.00 -al 4.58 -e 10 > output
```

The `std2` parameters (α , β , and a_x) for this range-separated hybrid functional are taken from Tab. 1 in Ref. 30.

Note that $\alpha^{(1)}$ given therein corresponds to β and $\beta^{(1)}$ to α (according to Eqs. 4 and 5). Thus for ω B97X, the parameter used to calculate γ_{AB}^J is $\beta = 8.00$.

To perform a sTD-DFT calculation with the same set-up, just add the `-rpa` flag:

```
std2 -f wb97x.molden.inp -ax 0.56 -be 8.00 -al 4.58 -e 10 -rpa > output
```

So far, five range-separated hybrid functionals were parametrized. The parameters are given below:

functional	a_x	α	β
CAM-B3LYP	0.38	0.90	1.86
LC-BLYP	0.53	4.50	8.00
ω B97	0.61	4.41	8.00
ω B97X	0.56	4.58	8.00
ω B97X-D3	0.51	4.51	8.00

3.3.3 Using a range-separated hybrid functional with XsTDA and XsTD-DFT schemes

If we have Molden input file from e.g. an ω B97X-D3 single-point calculation (here: `wb97xD3.molden.inp`), the respective XsTDA calculation can be performed as:

```
std2 -f wb97xD3.molden.inp -wb97XD3 -e 10 > output
```

For the XsTD-DFT calculation:

```
std2 -f wb97xD3.molden.inp -wB97XD3 -e 10 -rpa > output
```

4 The Spectrum Plotting Tool

Spectra may be plotted and visualized with the SpecDis program. Alternatively, we provide a processing tool called `g_spec`. It uses the file `tda.dat` (written by the `std2` program) as input. Run the tool as:

```
g_spec < tda.dat
```

It will generate two files, `spec.dat` and `rots.dat`. The first file contains the spectrum broadened by Gaussian curves, the latter one contains the pure oscillator/rotatory strengths that can be used to plot a stick spectrum.

The header of the `tda.dat` defines the options for `g_spec`. Important features are:

UV	Calculate absorption spectra (if not specified, CD is calculated)
VELO	Use the velocity representations of R and f (the latter if UV is also specified).
NM	Plot spectrum in nanometer scale instead of eV.
WIDTH	Half width at 1/e maximum of Gaussian curve (in eV).
SHIFT	Energy shift applied to whole spectrum (in eV).
LFAKTOR	Scaling factor for the stick spectrum printed to <code>rots.dat</code> .
RFAKTOR	Scaling factor for the broadended spectrum printed to <code>spec.dat</code> .

The Gaussian broadened spectrum (`spec.dat`) contains the molar extinction coefficient (for absorption) or molar circular dichroism (for CD) spectra, both given in units of $\text{L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$. The individual transition strengths are given in the same units in `rots.dat`. Note that by default `LFAKTOR` is set to 0.5, i.e., these are scaled down to allow easy plotting of broadened spectra with individual transition strengths.

5 Usage with GAUSSIAN

From version 1.3 on, the `std2` program can be interfaced with the GAUSSIAN program^[10] via the tool `g2molden`. This converts a GAUSSIAN output file into a Molden^[7] input file which is processable by the `std2` program. Make sure that the following keywords in your GAUSSIAN input file are set:

```

        #P   Additional printout (necessary for g2molden).
      ginput   Print out basis set information.
  pop=full or IOp(6/7=3)   Print out LCAO-MO coefficients.
        6D 10F   Use Cartesian basis to generate orbitals.

```

The last point is necessary since the std2 program can only handle Cartesian atomic orbitals. An exemplary input for the calculation with GAUSSIAN (on a water molecule) may look like this:

```
#P B3LYP/TZVP pop=full ginput 6D 10F
```

```
water singlepoint
```

```

O 1 xyz
H 0.000000 0.776483 -0.472981
H 0.000000 -0.776483 -0.472981
O 0.000000 0.000000 0.118245

```

After running the ground-state calculation with GAUSSIAN, you may convert the output file (termed `g09.log` here) into a Molden input file by:

```
g2molden g09.log > molden.input
```

The `molden.input` file may be used as an input file for the std2 program as described above (using `-sty 3`, see Sec. 3). If you encounter problems with the `g2molden` tool or the std2 program, feel free to contact us. However, we cannot give any support for problems related to GAUSSIAN itself.

6 Usage with Q-CHEM

A molden file can be automatically generated by Q-CHEM using the following arguments in the `$rem` section of your input file:

```

PRINT_ORBITALS = 2000000
MOLDEN_FORMAT = true
PURECART = 2222

```

`PRINT_ORBITALS` is the maximum number of orbitals printed, it needs to be very large to have all orbitals printed. `PURECART = 2222` specified that a Cartesian orbital basis set is used in the calculation. The molden file generated by Q-CHEM cannot be directly read by std2. The `qc2molden.sh` script extracts and converts the molden file. Just run `qc2molden.sh your_qchem_output` and a `molden.input` file is generated. The `-sty 3` argument needs to be used when running std2.

7 sTDA-xTB Procedure

The sTDA approach can be combined with a semi-empirical extended tight-binding (xTB) procedure for the ground state (for details see Ref. 14). The xTB calculation can be carried out with the standalone `xtb4stda` which can be obtained along with the necessary parameter files from our GitHub page.^[32]

7.1 xTB Options

The `xtb4stda` program then requires a geometry file (Xmol or TURBOMOLE coord) as input.

```
xtb4stda <coord>
```

The program will then write a binary file `wfn.xtb` which can be read from the `std2` program no additional input is required. For charged systems, a `.CHRG` file containing the molecular charge in the first line need to be present in the local directory. Similarly for open-shell systems, the number of unpaired electrons can be specified in the `.UHF` file. For additional options, run the `xtb4stda` program with the `-h` flag.

7.2 sTDA based on xTB

After running the ground state calculation with xTB, the `std2` program can be used to compute the excited states via:

```
std2 -xtb -e 10
```

This will read the `wfn.xtb` file in the working directory and compute all excited states up to 10 eV. The method-specific parameters α , β , and a_x are set automatically. Due to computational efficiency, we recommend to use the Tamm-Dancoff approximated variant (i.e., sTDA-xTB) although the full linear response (i.e., sTD-DFT-xTB) treatment may be invoked with the `-rpa` flag. Due to the $A+B/2$ correction,^[14] which is invoked by default in `std2`, even electronic circular dichroism spectra in the origin independent dipole velocity formalism may be computed reasonably well with sTDA-xTB.

Note that XsTD methods cannot use an xTB ground state for the moment.

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