

User guide

$\mathcal{H}\Phi$ ver. 0.1

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1

What is $\mathcal{H}\Phi$?

1.1 What is $\mathcal{H}\Phi$?

Comparison between experimental observation and theoretical analysis is a crucial step in condensed-matter physics research. Temperature dependence of specific heat and magnetic susceptibility, for example, have been studied to extract nature of low energy excitations of and magnetic interactions among electrons, respectively, through comparison with theories such as Landau's Fermi liquid theory and Curie-Weiss law.

For the flexible and quantitative comparison with experimental data, an exact diagonalization approach [1] is one of the most reliable numerical tools without any approximation or inspiration of genius. For last few decades, a numerical diagonalization package for quantum spin hamiltonians, TITPACK developed by Prof. Hidetoshi Nishimori in Tokyo Institute of Technology, has been widely used in the condensed-matter physics community. Nevertheless, limitation of computational resources had hindered the non-expert users from applying the package to quantum systems with large number of electrons or spins.

In contrast, recent and rapid development of parallel computing infrastructure opens up new avenues for user-friendly larger scale diagonalizations up to 18 site Hubbard clusters or 36 $S=1/2$ quantum spins. In addition, recent advances in quantum statistical mechanics [2–5] enable us to calculate finite temperature properties of quantum many-body systems with computational costs similar to calculations of ground state properties, which also enables us to compare theoretical results for temperature dependence of, for example, specific heat and magnetic susceptibility with experimental results quantitatively [6]. To utilize the parallel computing infrastructure with narrow bandwidth and distributed-memory architectures, efficient, user-friendly, and highly parallelized diagonalization packages are highly desirable.

$\mathcal{H}\Phi$, a flexible diagonalization package for solving quantum lattice hamiltonians, has been developed to be such a descendant of the pioneering package TITPACK. The Lanczos method for calculations of the ground state and a few excited states properties, and finite temperature calculations based on thermal pure quantum states [5] are implemented in the package $\mathcal{H}\Phi$, with an easy-to-use and flexible user interface. By using $\mathcal{H}\Phi$, you can analyze a wide range of quantum lattice hamiltonians including simple Hubbard and Heisenberg models, multi-band extensions of the Hubbard model, exchange couplings that break $SU(2)$ symmetry of quantum spins such as Dzyaloshinskii-Moriya and Kitaev interactions, and Kondo lattice models describing itinerant electrons coupled with quantum spins. $\mathcal{H}\Phi$ calculates a variety of physical quantities such as internal energy at zero temperature or

finite temperatures, temperature dependence of specific heat, charge/spin structure factors, and so on. A broad spectrum of users including experimental scientists is cordially welcome.

1.1.1 License

The distribution of the program package and the source codes for $\mathcal{H}\Phi$ follow GNU General Public License version 3 (GPL v3).

1.1.2 Copyright

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This software is developed under the support of “*Project for advancement of software usability in materials science*” by The Institute for Solid State Physics, The University of Tokyo.

1.1.3 Contributors

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- ver.0.1 (released at 2015/10/09)
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1.2 Operating environment

$\mathcal{H}\Phi$ is tested in the following platforms:

- The supercomputer system-B “sekirei” and system-C “maki” in ISSP

- Linux PC + intel compiler
- Linux PC + gcc
- Mac + gcc

2

How to use $\mathcal{H}\Phi$?

2.1 Prerequisite

$\mathcal{H}\Phi$ requires the following packages:

- C compiler (intel, Fujitsu, GNU, etc.)
- LAPACK library (intel MKL, Fujitsu TCL, ATLAS, etc.)

Tips

E. g. / Settings of intel compiler

When you use the intel compiler, you can use easily scripts attached to the compiler. In the case of the bash in 64 bit OS, write the following in your `~/.bashrc`:

```
source /opt/intel/bin/compilervars.sh intel64
```

or

```
source /opt/intel/bin/iccvars.sh intel64
```

```
source /opt/intel/mkl/bin/mklvars.sh
```

Please read manuals of your compiler/library for more information.

2.2 Installation

You can download $\mathcal{H}\Phi$ in the following place.

<https://github.com/QLMS/HPhi/releases>

You can obtain the $\mathcal{H}\Phi$ directory by typing

```
$ tar xzvf HPhi-xxx.tar.gz
```

There are two kind of procedures to install $\mathcal{H}\Phi$.

2.2.1 Using `HPhiconfig.sh`

Please run `HPhiconfig.sh` script in the $\mathcal{H}\Phi$ directory as follow (for ISSP system-B "sekirei"):


```
$ bash HPhiconfig.sh sekirei
```

Then environmental configuration file `make.sys` is generated in `src/` directory. The command-line argument of `HPhiconfig.sh` is as follows:

- `sekirei` : ISSP system-B "sekirei"
- `maki` : ISSP system-C "maki"
- `intel` : intel compiler + Linux PC
- `gcc` : GCC + Linux PC
- `gcc-mac` : GCC + Mac

`make.sys` is as follows (for ISSP-system-B "sekirei"):

```
CC = icc
LAPACK_FLAGS = -Dlapack -mkl=parallel
FLAGS = -qopenmp -O3 -xCORE-AVX2 -mcmmodel=large -shared-intel
MTFLAGS = -DDSFMT_MEXP=19937 $(FLAGS)
INCLUDE_DIR=./include
```

We explain macros of this file as:

- `CC` : The Compilation command (`icc`, `gcc`, `fccpx`)
- `LAPACK_FLAGS` : Compilation options for LAPACK. `-Dlapack` can not be removed.
- `FLAGS` : Other compilation options. OpenMP utilization option (`-openmp`, `-fopenmp`, `-qopenmp`, etc.) must be specified.
- `MTFLAGS`, `INCLUDE_DIR` : Options for the Mersenne Twister and additional include directory. You do not have to modify them.

Then you are ready to compile HPhi. Please type

```
$ make HPhi
```

and obtain an executable HPhi in `src/` directory; you should add this directory to the `$PATH`.

2.2.2 Using cmake

Tips

You can make a PATH to $\mathcal{H}\Phi$ as follows:

```
$ export PATH=${PATH}:HPhi_top_directory/src/
```

If you keep this PATH, you should write above in `~/.bashrc` (for `bash` as a login shell)

2.3 Directory structure

When HPhi-xxx.tar.gz is unzipped, the following directory structure is composed.

```

COPYING
doc/
  en/
  jp/
  userguide_en.pdf
  userguide_jp.pdf
HPhiconfig.sh
samples/
  Expert/
    Hubbard/
      square/
        *.def
        output_FullDiag/
          **.dat
        output_Lanczos/
          **.dat
        output_TPQ/
          **.dat
      triangular/
        ...
    Kondo/
      chain/
        ...
    Spin/
      HeisenbergChain/
        ...
      HeisenbergSquare/
        ...
      Kitaev/
        ...
  Standard/
    Hubbard/
      square/
        StdFace.def
        output_FullDiag/
          **.dat
        output_Lanczos/
          **.dat
        output_TPQ/
          **.dat

```

```

        triangular/
            ...
Kondo/
    chain/
        ...
Spin/
    HeisenbergChain/
        ...
    HeisenbergSquare/
        ...
    Kitaev/
        ...
src/
    *.c
    include/
        *.h
    makefile_src

```

2.4 Basic usage

$\mathcal{H}\Phi$ has two modes; standard mode and expert mode. Here, the basic flows of calculations by standard and expert modes are shown.

2.4.1 *Standard mode*

The procedure of calculation through the standard mode is shown as follows:

1. Make a directory for a calculation scenario.

First, you make a working directory for the calculation.

2. Make input files for standard mode

In the standard mode, you can choose a model (the Heisenberg model, the Hubbard model, etc.) and a lattice (the square lattice, the triangular lattice, etc.) from ones provided; you can specify some parameters (such as the first/second nearest neighbor hopping integrals, the on-site Coulomb integral, etc.) for them. Finally, you have to specify the numerical method (such as the Lanczos method) employed in this calculation. The input file format is described in the Sec. 4.

3. Run

Run a executable `HPhi` in terminal by setting option “`-s`” (or “`--standard`”) and the name of input file written in previous step.

```
$ Path/HPhi -s Input_file_name
```

4. Watch calculation logs

Log files are outputted in the “output” folder which is automatically made in the directory for a calculation scenario. The details of output files are shown in 4.3.

5. Results

If the calculation is finished normally, the result files are outputted in the “output” folder. The details of output files are shown in 4.3.

Tips

The number of threads for OpenMP

If you specify the number of OpenMP threads for $\mathcal{H}\Phi$, you should set it as follows (in case of 16 threads) before the running:

```
export OMP_NUM_THREADS=16
```

2.4.2 Expert mode

The procedure of calculation for expert mode is shown as follows.

1. Make a directory for a calculation scenario.

First, you make a directory named as a calculation scenario (you can attach an arbitrary name to a directory).

2. Make input files for expert mode

For expert mode, you should make input files for constructing Hamiltonian operators, calculation condition and a list file for the filenames of input files (see the file formats shown in 4.2).

Note: A List file can be easily made by using standard mode.

3. Run

Run $\mathcal{H}\Phi$ in terminal by setting option “-e” (or “--expert”) and a file name of a list file.

```
$ Path/HPhi -e Input_List_file_name
```

4. Under running

Log files are outputted in the “output” folder which is automatically made in the directory for a calculation scenario. The details of output files are shown in 4.3.

5. Results

If the calculation is finished normally, the result files are outputted in the “output” folder. The details of output files are shown in 4.3.

3

Tutorial

3.1 Common works

In this section, we describe the procedure for constructing calculation environments after installation.

1. Make a directory for a calculation scenario.
2. Move to the directory.

Here, we show a simple example for commands on a terminal below.

```
mkdir ./CalcScenario
mv ./CalcScenario
```

3.2 *Standard mode*

3.2.1 Heisenberg model

This tutorial should be performed in

`samples/Standard/Spin/HeisenbergChain/`

The input file, reference outputs, and the redirected standard output are provided as follows:

```
samples/Standard/Spin/HeisenbergChain/StdFace.def
samples/Standard/Spin/HeisenbergChain/output_FullDiag/
samples/Standard/Spin/HeisenbergChain/output_Lanczos/
samples/Standard/Spin/HeisenbergChain/output_TPQ/
samples/Standard/Spin/HeisenbergChain/FullDiag.out
samples/Standard/Spin/HeisenbergChain/Lanczos.out
samples/Standard/Spin/HeisenbergChain/TPQ.out
```

In this case, we treat the one dimensional antiferromagnetic Heisenberg chain which has a nearest neighbor spin coupling.

$$\hat{H} = J \sum_{i=1}^{N_{\text{site}}} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_{i+1} \quad (3.1)$$

The input file is as follows:

```
L = 16
model = "Spin"
method = "Lanczos"
lattice = "chain lattice"
J = 1.0
2Sz = 0
```

In this tutorial, J and the number of sites are set to 1 (arbitral unit) and 16 respectively.

Log output

Log messages are outputted to the standard output. Log files for calculation procedure are made in "output" directory which is automatically created. In this example, the following files are outputted.

```
CHECK_InterAll.dat      Time_CG_EigenVector.dat  zvo_Lanczos_Step.dat
CHECK_Memory.dat        WarningOnTransfer.dat    zvo_sz_TimeKeeper.dat
CHECK_Sdim.dat          zvo_TimeKeeper.dat
```

The details for the outputted files are shown in 4.3.1-4.3.10.

We execute

```
$ Path/HPhi -s StdFace.def
```

and obtain following standard outputs:

```
##### Standard Interface Mode STARTS #####
```

```
Open Standard-Mode Inputfile StdFace.def
```

```
KEYWORD : 1                | VALUE : 16
KEYWORD : model             | VALUE : spin
KEYWORD : method            | VALUE : lanczos
KEYWORD : lattice           | VALUE : chainlattice
KEYWORD : j                 | VALUE : 1.0
KEYWORD : 2sz               | VALUE : 0
```

```
##### Parameter Summary #####
```

```
          L = 16
          a = 1.00000      ##### DEFAULT VALUE IS USED #####
```

(Partly omitted)

```
          2Sz = 0
ioutputmode = 1          ##### DEFAULT VALUE IS USED #####
```

Print Expart input files

```

    zlocspn.def is written.
    zTrans.def is written.
  zInterAll.def is written.
  namelist.def is written.
    calcmmod.def is written.
    modpara.def is written.
  greenone.def is written.
  greentwo.def is written.

```

Input files are generated.

```

Start: Read File 'namelist.def'.
End: Read File 'namelist.def'.
Read File 'calcmmod.def' for CalcMod.
Read File 'modpara.def' for ModPara.
Read File 'zlocspn.def' for LocSpin.
Read File 'zTrans.def' for Trans.
Read File 'zInterAll.def' for InterAll.
Read File 'greenone.def' for OneBodyG.
Read File 'greentwo.def' for TwoBodyG.
Definition files are correct.
Read File 'zlocspn.def'.
Nsite= 16.
Read File 'zTrans.def'.
Read File 'zInterAll.def'.
Read File 'greenone.def'.
Read File 'greentwo.def'.
comb_sum= 12870
MAX DIMENSION idim_max=12870
REQUIRED MEMORY  max_mem=0.000618 GB
sdim=256 =2^16
Indices and Parameters of Definition files(*.def) are complete.
LARGE ALLOCATE FINISH !
EDTrans EDNTransfer=0
EDTrans EDNChemi=0
Start: Calc Sz.
idim=65536.000000  irght=255  ilft=65280  ihfbit=256
num_threads==2
Xicnt=12870
End  : Calc Sz.
Start: calc diagaonal components of Hamiltonian.
End  : calc diagaonal components of Hamiltonian.
Start: Calculate Lanczos Eigenvalue.

```

```

initial_mode=0 normal: iv = 6436 i_max=12870 k_exct =1
stp=4 -0.2423006825 1.4795269690 2.8204808612 3.5851499951
stp=6 -1.5930861352 -0.0869006048 1.2794492426 2.3323141732
stp=8 -2.7742729206 -1.2848359197 -0.1095390623 1.0439243217

```

(partly omitted)

```

stp=60 -7.1422963606 -6.6965474266 -6.5234070574 -6.2986527242
stp=62 -7.1422963606 -6.6965474266 -6.5234070574 -6.2986527253
End : Calculate Lanczos EigenValue.
Start: Calculate Lanczos Eigenvector.
End: Calculate Lanczos Eigenvector.
Start: Calculate Energy.
End : Calculate Energy by Lanczos method.
energy=-7.142296

```

Accuracy check !!!

```

-7.1422963606167746 -7.1422963606168191: diff_ere=0.000000000 ...
Accuracy of Lanczos vector is enough

```

In the beginning of this run, files describing the detail of considered Hamiltonian (`zlocspin.def`, `zTrans.def`, `zInterAll.def`, `namelist.def`, `calcmmod.def`, `modpara.def`) and files specifying elements of correlation functions that will be calculated (`greenone.def`, `greentwo.def`) are generated.

Outputs for calculation results

Lanczos method

When a calculation by Lanczos method is finished normally, eigenenergies, one-body Green's functions and two-body Green's functions are calculated and outputted to the files, respectively. In this sample, following files are outputted.

```

zvo_energy.dat zvo_cisajs.dat
zvo_cisajsckalt.dat

```

For standard mode, all pairs of $\langle n_{i\sigma} \rangle$ are calculated as one-body Green's functions and those of $\langle n_{i\sigma} n_{j\sigma'} \rangle$ are calculated as two-body Green's functions on the basis of the definition files, `greenone.def` and `greentwo.def`.

When accuracy of Lanczos vectors is enough, one-body and two-body Green's functions are calculated by eigenvectors obtained by Lanczos method. While accuracy of Lanczos vectors is *not* enough, a message "Accuracy of Lanczos vector is not enough" is outputted to the standard output and one-body and two-body Green's functions are calculated by eigenvectors obtained by CG method. The details of output files are shown in 4.3.11, 4.3.17, 4.3.18.

TPQ method

When `method="TPQ"` is selected in an input file, a calculation by TPQ method is started. After finishing of the calculation normally, following files are outputted, where `%%` is a number of run and `&&` is a number of steps for TPQ method.

```
Norm_rand%%.dat SS_rand%%.dat
zvo_cisajs_set%%step&&.dat
zvo_cisajscktalt_set%%step&&.dat
```

In `Norm_rand%%.dat`, basic informations such as inverse of temperature and a norm of wave function before normalization are outputted with a TPQ step for each number of runs. In `SS_rand%%.dat`, physical quantities such as inverse of temperature, energy and expected value of square of Hamiltonian are outputted with a TPQ step for each number of runs. In `zvo_cisajs_set%%step&&.dat` and `zvo_cisajscktalt_set%%step&&.dat`, one-body and two-body Green's functions are outputted for each number of a TPQ steps and runs. The details of these files are shown in 4.3.13, 4.3.14, 4.3.17, 4.3.18.

Full diagonalization method

When `method = "fulldiag"` is selected in an input file, a calculation by Full diagonalization method is started. After finishing of the calculation normally, following files are outputted, where `xx` is a number of an eigenstate counting from 0.

```
Eigenvalue.dat zvo_cisajs_eigen_xx.dat
zvo_cisajscktalt_eigen_xx.dat zvo_phys_Nup4_Ndown4.dat
```

In `Eigenvalue.dat`, an eigennumber and an eigenvalue are outputted for each lines. In `zvo_cisajs_eigen_xx.dat` and `zvo_cisajscktalt_eigen_xx.dat`, one-body Green's functions and two-body Green's functions are outputted for each eigen-number. In `zvo_phys_Nup4_Ndown4.dat`, physical quantities such as expected values of energy and doublon are outputted. The details of these files are shown in 4.3.15 - 4.3.18.

3.2.2 Other tutorials

There are following tutorials in `samples/Standard/`.

- The Hubbard model on the two dimensional square lattice
(`samples/Standard/Hubbard/square/`)
- The Hubbard model on the two dimensional triangular lattice
(`samples/Standard/Hubbard/triangular/`)
- The one dimensional Kondo chain
(`samples/Standard/Kondo/chain/`)

- The one dimensional antiferromagnetic Heisenberg chain
(samples/Standard/Spin/HeisenbergChain/HeisenbergChain/)
- The antiferromagnetic Heisenberg model on the two dimensional square lattice
(samples/Standard/Spin/HeisenbergSquare/)
- The Kitaev model with 2×3 unit cells to Honeycomb lattice
(samples/Standard/Spin/Kitaev/)

We can perform these tutorials in the same way to the previous one.

3.3 *Expert mode*

For expert mode, following input files are needed

1. A file list for input files,
2. Files for basic parameters,
3. Files for constructing Hamiltonian,
4. Files for setting output components.

The process after calculation is same as standard mode. In this section, we show the demonstration for one dimensional antiferromagnetic Heisenberg chain model which has a nearest neighbor spin coupling,

$$H = \sum_{i=0}^{15} J \mathbf{S}_i \cdot \mathbf{S}_{i+1}, \quad (3.2)$$

where $J = 2$, $\mathbf{S}_{16} = \mathbf{S}_0$.

We use following input files in samples/Expert/Spin/HeisenbergChain.

```
calcmmod.def    greentwo.def    namelist.def    zTrans.def
greenone.def    modpara.def    zInterAll.def   zlocspn.def
```

3.3.1 A file list for input files

In namelist.def, kinds of input files and filenames are defined as shown below. By writing keyword and filenames at each lines, kinds of files are distinguished. The details for namelist.def are shown in 4.2.1.

```
CalcMod calcmmod.def
ModPara modpara.def
LocSpin zlocspn.def
Trans zTrans.def
InterAll zInterAll.def
OneBodyG greenone.def
TwoBodyG greentwo.def
```

3.3.2 Files for basic parameters

In this subsection, we show the way to set a calculation mode, parameters for calculation and positions of localized spins.

Setting a calculation mode

Calculation mode is set in a CalcMod file (in this sample file, calcmod.def). The contents of files are shown as below.

```
#CalcType = 0:Lanczos, 1:TPQCalc, 2:FullDiag
#CalcMod = 0:Hubbard, 1:Spin, 2:Kondo, 3:HubbardGC,
4:SpinGC, 5:KondoGC
CalcType    0
CalcModel   1
```

We select a calculation method by CalcType and a target model by CalcModel. In this sample, we set Lanczos method as a calculation method and a target model as a spin system (canonical ensemble). The details of a CalcMod file are shown in 4.2.2.

Setting parameters for calculation

Parameter for calculation are set in a ModPara file (in this sample, modpara.def). The contents of files are shown as below.

```
-----
Model_Parameters    0
-----
VMC_Cal_Parameters
-----
CDataFileHead  zvo
CParaFileHead  zqp
-----
Nsite          16
Nup             8
Ndown          8
Lanczos_max    1000
initial_iv     12
nvec           1
exct           1
LanczosEps     14
LanczosTarget  2
LargeValue     12
NumAve         5
ExpecInterval  20
```

In this file, we set parameters for calculation such as a site number, a to-

tal number of up spin, a total number of down spin and a number of Lanczos step etc. The details of ModPara file are shown in 4.2.3.

Setting positions of localized spins

Positions of localized spins are defined by a LocSpin file (in this sample, locspn.def). The contents of files are shown as below.

```
=====
NlocalSpin      16
=====
=====i_0LocSpn_1IteElc =====
=====
      0      0
      1      0
      2      0
      3      0
      4      0
      5      0
      ...
```

When CalcModel in a CalcMod file is set as spin system, all sites automatically treated as localized spins. The details of a LosSpn file is shown in 4.2.4.

3.3.3 Files for constructing Hamiltonian

After setting basic parameters, we make input files for constructing Hamiltonian. Since calculations are done by the representation of fermion operators in $\mathcal{H}\Phi$, we must rewrite spin operator using the following relation

$$S_z^{(i)} = (c_{i\uparrow}^\dagger c_{i\uparrow} - c_{i\downarrow}^\dagger c_{i\downarrow})/2, \quad (3.3)$$

$$S_+^{(i)} = c_{i\uparrow}^\dagger c_{i\downarrow}, \quad (3.4)$$

$$S_-^{(i)} = c_{i\downarrow}^\dagger c_{i\uparrow}. \quad (3.5)$$

Setting transfer integrals

In a Trans file (in this sample, zTrans.def), we set a transfer part of Hamiltonian,

$$H_+ = - \sum_{ij\sigma_1\sigma_2} t_{ij\sigma_1\sigma_2} c_{i\sigma_1}^\dagger c_{j\sigma_2}. \quad (3.6)$$

The contents of files are shown as below.

```
=====
NTransfer        0
=====
=====i_j_s_tijs=====
=====
```

We can use this term when an electric magnetic field is added in spin system. For example, when an magnetic field is added at a site 1 such as $-0.5S_z^{(1)}$, this term can be rewritten as $-0.5/2(c_{1\uparrow}^\dagger c_{1\uparrow} - c_{1\downarrow}^\dagger c_{1\downarrow})$. Thus, the input file becomes as follows.

```
=====
NTransfer      1
=====
=====i_j_s_tijs=====
=====
1 0 1 0 -0.25 0
1 1 1 1 0.25 0
```

The details for a Trans file are shown in 4.2.5.

Setting general two-body interactions

In an InterAll file (in this sample, zInterall.def), we set a general two-body interaction part of Hamiltonian,

$$H+ = \sum_{i,j,k,l} \sum_{\sigma_1,\sigma_2,\sigma_3,\sigma_4} I_{ijkl\sigma_1\sigma_2\sigma_3\sigma_4} c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4}. \quad (3.7)$$

The contents of files are shown as below.

```
=====
NInterAll      96
=====
=====zInterAll=====
=====
0      0      0      0      1      0      1      0      0.500000  0.000000
0      0      0      0      1      1      1      1     -0.500000  0.000000
0      1      0      1      1      0      1      0     -0.500000  0.000000
0      1      0      1      1      1      1      1      0.500000  0.000000
0      0      0      1      1      1      1      0      1.000000  0.000000
0      1      0      0      1      0      1      1      1.000000  0.000000
...
```

Here, we explain an interaction between a site i and a site j , for simplicity. Using fermion operators, interaction terms for spin operators can be rewritten as

$$\begin{aligned} H_{i,i+1} &= J(S_x^{(i)} S_x^{(i+1)} + S_y^{(i)} S_y^{(i+1)} + S_z^{(i)} S_z^{(i+1)}) \\ &= J \left(\frac{1}{2} S_+^{(i)} S_-^{(i+1)} + \frac{1}{2} S_-^{(i)} S_+^{(i+1)} + S_z^{(i)} S_z^{(i+1)} \right) \\ &= J \left[\frac{1}{2} c_{i\uparrow}^\dagger c_{i\downarrow} c_{i+1\downarrow}^\dagger c_{i+1\uparrow} + \frac{1}{2} c_{i\downarrow}^\dagger c_{i\uparrow} c_{i+1\uparrow}^\dagger c_{i+1\downarrow} + \frac{1}{4} (c_{i\uparrow}^\dagger c_{i\uparrow} - c_{i\downarrow}^\dagger c_{i\downarrow}) (c_{i+1\uparrow}^\dagger c_{i+1\uparrow} - c_{i+1\downarrow}^\dagger c_{i+1\downarrow}) \right]. \end{aligned}$$

Thus, the interaction $S_z^{(i)} S_z^{(i+1)}$ for $J = 2$ can be written as

i	0	i	0	i+1	0	i+1	0	0.500000	0.000000
i	0	i	0	i+1	1	i+1	1	-0.500000	0.000000
i	1	i	1	i+1	0	i+1	0	-0.500000	0.000000
i	1	i	1	i+1	1	i+1	1	0.500000	0.000000

in the format of an InterAll file. The other terms can be written as below.

i	0	i	1	i+1	1	i+1	0	1.000000	0.000000
i	1	i	0	i+1	0	i+1	1	1.000000	0.000000

There are other file formats for constructing Hamiltonian. The details for input formats of two-body interactions are shown in 4.2.6-4.2.13.

3.3.4 Setting output components

In OneBodyG and TwoBodyG files, calculating components for one-body and two-body Green's functions are defined, respectively.

Setting calculating components for one-body Green's functions

In a OneBodyG file (in this sample, greenone.def), calculating components for $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} \rangle$ are defined. The contents of files are shown as below.

```
=====
NCisAjs          32
=====
===== Green functions =====
=====
  0      0      0      0
  0      1      0      1
  1      0      1      0
  1      1      1      1
  2      0      2      0
  ...
```

The details for input formats of a OneBodyG file are shown in 4.2.14.

Setting calculating components for two-body Green's functions

In a TwoBodyG file (in this sample, greentwo.def), calculating components for $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4} \rangle$ are defined. The contents of files are shown as below.

```

=====
NCisAjsCktAltDC          1024
=====
===== Green functions for Sq AND Nq =====
=====
      0      0      0      0      0      0      0      0
      0      0      0      0      0      1      0      1
      0      0      0      0      1      0      1      0
      0      0      0      0      1      1      1      1
      0      0      0      0      2      0      2      0
      ...

```

The details for input formats of a TwoBodyG file are shown in 4.2.15.

3.3.5 Running

After making all input files above, we ready to run a program. For expert mode, we must set an option “-e” and a file name list (in this sample, namelist.def) as arguments to run $\mathcal{H}\Phi$.

```
$ Path/HPhi -e namelist.def
```

The process after calculating is same as that of standard mode.

3.3.6 Other tutorials

There are following tutorials in `samples/Expert/`.

- The Hubbard model on the two dimensional square lattice
(`samples/Expert/Hubbard/square/`)
- The Hubbard model on the two dimensional triangular lattice
(`samples/Expert/Hubbard/triangular/`)
- The one dimensional Kondo chain
(`samples/Expert/Kondo/chain/`)
- The one dimensional antiferromagnetic Heisenberg chain
(`samples/Expert/Spin/HeisenbergChain/HeisenbergChain/`)
- The antiferromagnetic Heisenberg model on the two dimensional square lattice
(`samples/Expert/Spin/HeisenbergSquare/`)
- The Kitaev model with 2×3 unit cells to Honeycomb lattice
(`samples/Expert/Spin/Kitaev/`)

We can perform these tutorials in the same way to the previous one.

3.4 Making input files for *Expert* mode

This mode is to make input files for *Expert* mode. A set of input files made by this mode gives a model provided in *Standard* mode. The usage is shown as below.

1. Make an input file for *Standard* mode.
2. Setting an option “-sdry” and an input file (in this example, StdFace.def), run $\mathcal{H}\Phi$.

```
$ Path/HPhi -sdry StdFace.def
```

3. Following files are made as input files for *Expert* mode in the present working directory.

calcm0d.def	greentwo.def	namelist.def	zTrans.def
greenone.def	modpara.def	zInterAll.def	zlocspn.def

4

File specification

4.1 Input files for *Standard mode*

An example of input file for the standard mode is shown below:

```
W = 2
L = 4
model = "spin"
method = "Lanczos"

lattice = "triangular lattice"
//mu = 1.0
// t = -1.0
// t' = -0.5
// U = 8.0
//V = 4.0
//V'=2.0
J = -1.0
J'=-0.5
// nelec = 8
2Sz = 0
```

Basic rules for input files

- In each line, there is a set of a keyword (before an “=”) and a parameter(after an “=”); they are separated by “=”.
- You can describe keywords in a random order.
- Empty lines and lines beginning in a “//”(comment outs) are skipped.
- Upper- and lowercase are not distinguished. Double quotes and blanks are ignored.
- There are three kinds of parameters.
 1. Parameters that must be specified (if not, $\mathcal{H}\Phi$ will stop with error messages),
 2. Parameters that is not necessary be specified (if not, default values are used),
 3. Parameters that must not be specified (if specified, $\mathcal{H}\Phi$ will stop with error messages).

An example of 3 is transfer t for the Heisenberg spin system. If you choose “model=spin”, you should not specify “ t ”.

We explain each keywords as follows:

4.1.1 Parameters about the kind of a calculation

- **model**

Type : String (Choose from "Fermion Hubbard", "Spin", "Kondo Lattice", "Fermion HubbardGC", "SpinGC", "Kondo LatticeGC")^{*1}

Description : The target model is specified with this parameter; above words denote the canonical ensemble of the Fermion in the Hubbard model

$$H = -\mu \sum_{i\sigma} c_{i\sigma}^\dagger c_{i\sigma} - \sum_{i \neq j\sigma} t_{ij} c_{i\sigma}^\dagger c_{j\sigma} + \sum_i U n_{i\uparrow} n_{i\downarrow} + \sum_{i \neq j} V_{ij} n_i n_j, \quad (4.1)$$

canonical ensemble in the Kitaev-Heisenberg model

$$H = -h \sum_i S_{iz} + \Gamma \sum_i S_{ix} + D \sum_i S_{iz} S_{iz} + \sum_{ij} (J_{ijx} S_{ix} S_{jx} + J_{ijy} S_{iy} S_{jy} + J_{ijz} S_{iz} S_{jz}), \quad (4.2)$$

canonical ensemble in the Kondo lattice model

$$H = -\mu \sum_{i\sigma} c_{i\sigma}^\dagger c_{i\sigma} - t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^\dagger c_{j\sigma} + \frac{J}{2} \sum_i \left\{ S_i^+ c_{i\downarrow}^\dagger c_{i\uparrow} + S_i^- c_{i\uparrow}^\dagger c_{i\downarrow} + S_{iz} (n_{i\uparrow} - n_{i\downarrow}) \right\}, \quad (4.3)$$

grand canonical ensemble of the Fermion in the Hubbard model [Eqn. (4.1)], grand canonical ensemble in the Kitaev-Heisenberg model [Eqn. (4.2)], and grand canonical ensemble in Kondo lattice model [Eqn. (4.3)] respectively.

- **method**

Type : String (Choose from "Lanczos", "TPQ", "Full Diag")

Description : The calculation type is specified with this parameter; above words denote the single eigenstate calculation by using the Lanczos method, at the finite-temperature by thermally pure quantum state, and the full diagonalization method, respectively.

- **lattice**

Type : String (Choose from "Chain Lattice", "Square Lattice", "Triangular Lattice", "Honeycomb Lattice")

^{*1}GC=Grand Canonical

Description : The lattice shape is specified with this parameter; above words denote the one dimensional chain lattice (Fig. 4.1(a)), the two dimensional square lattice (Fig. 4.1(b)), the two dimensional triangular lattice (Fig. 4.1(c)), and the two dimensional anisotropic honeycomb lattice (Fig. 4.2), respectively.

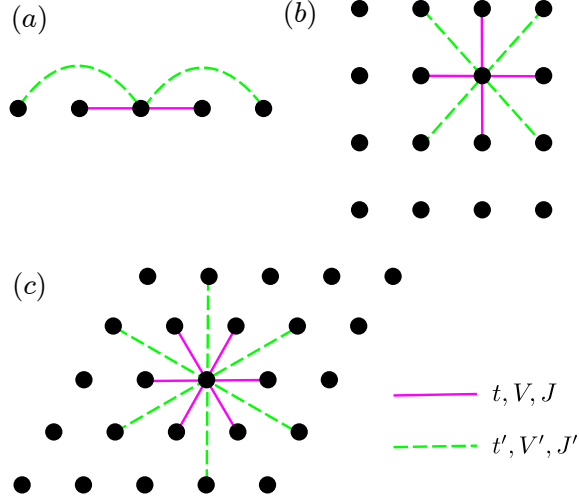


Figure 4.1: Schematic illustration of (a) one dimensional chain lattice, (b) two dimensional square lattice, and (c) two dimensional triangular lattice. They have t , V , and J as a nearest neighbor hopping, an offsite Coulomb integral, and a spin-coupling constant, respectively (magenta solid lines); They also have t' , V' , and J' as a next nearest neighbor hopping, offsite Coulomb integral, and spin-coupling constant, respectively (green dashed line).

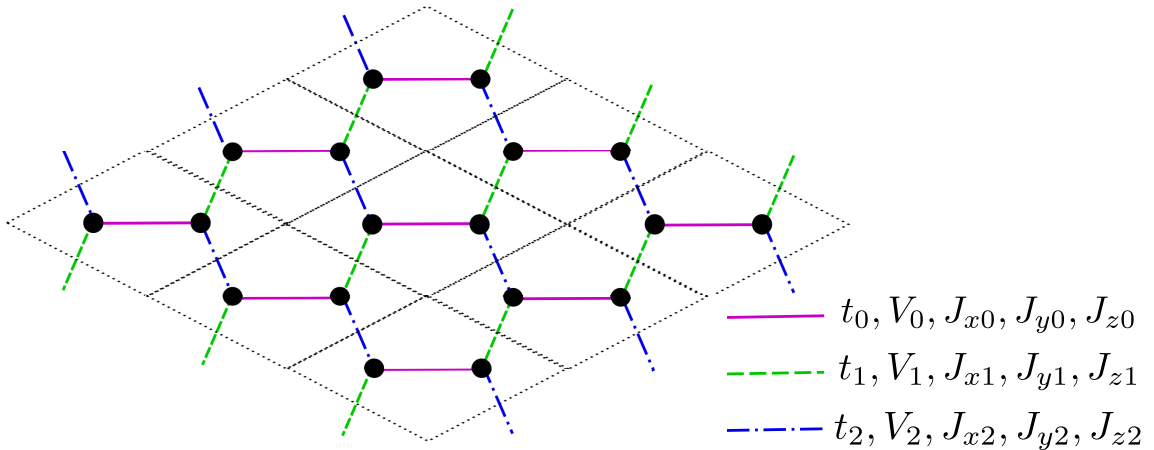


Figure 4.2: Schematic illustration of the anisotropic honeycomb lattice. The nearest neighbor hopping integral, spin coupling, offsite Coulomb integral depend on the bond direction. Those between second nearest neighbor sites are not supported.

4.1.2 Parameters for the lattice

- L

Type : Positive integer

Description : The number of sites along the first dimensional direction is specified with this parameter.

- W

Type : Positive integer

Description : The number of sites along the second dimensional direction is specified with this parameter. When `lattice = "Chain Lattice"`, it should not be specified because it will not be used (if specified, $\mathcal{H}\Phi$ will stop).

- a

Type : Real (1.0 as a default)

Description : The lattice constant is specified with this parameter.

4.1.3 Parameters for conserved quantities

- nelec

Type : Positive integer

Description : The number of valence electrons is specified with this parameter. When `lmodel = "Fermion HubbardGC", "Spin", or "SpinGC"`, it should not be specified.

- 2Sz

Type : Integer

Description : The z component of the twofold total spin is specified with this parameter. When `lmodel = "Fermion HubbardGC" or SpinGC`, it should not be specified.

4.1.4 Parameters for the Hubbard model

- mu

Type : Real (0.0 as a default)

Description : The chemical potential μ (including the site potential) is specified with this parameter.

- t

Type : Real (1.0 as a default)

Description : The nearest neighbor hopping t (See Fig. 4.1) is specified with this parameter.

- t'
Type : Real (0.0 as a default)
Description : The second nearest neighbor hopping t' (See Fig. 4.1) is specified with this parameter.
- t_0, t_1, t_2
Type : Real (t as defaults)
Description : The nearest neighbor hopping in the anisotropic honeycomb lattice (See Fig. 4.2) is specified with this parameter.
- U
Type : Real (0.0 as a default)
Description : The onsite Coulomb integral U is specified with this parameter.
- V, V'
Type : Real (0.0 as defaults)
Description : The nearest neighbor offsite Coulomb integrals V and the second nearest neighbor offsite Coulomb integrals V' (Fig. 4.1) are specified with these parameters.
- V_0, V_1, V_2
Type : Real (V as defaults)
Description : Nearest neighbor offsite Coulomb integrals on the anisotropic honeycomb lattice (Fig. 4.2) are specified with these parameters.

4.1.5 Parameters for the Kitaev-Heisenberg model

- h, Gamma, D
Type : Real (0.0 as a default)
Description : The longitudinal magnetic field, transverse magnetic field, and the single-site anisotropy parameter are specified with these parameters.
- J
Type : Real (1.0 as a default)
Description : The isotropic spin-coupling constant between nearest neighbor sites (See Fig. 4.1) is specified with this parameter. J_x, J_y, J_z , and J_{xy} are set to J if J is specified AND none of J_x, J_y, J_z and J_{xy} is specified.
- J_z, J_{xy}
Type : Real (J as a default)
Description : The uniaxially anisotropic spin-coupling constant between nearest neighbor sites (See Fig. 4.1) is specified with this parameter. J_x and J_y are set to J_{xy} if J_{xy} is specified AND none of J_x and J_y is specified.

- J_x, J_y

Type : Real (J_{xy} as a default)

Description : The fully anisotropic spin-coupling constant between nearest neighbor sites (See Fig. 4.1) is specified with this parameter.

- $J', J_x', J_y', J_z', J_{xy}'$

Type : Real (J', J_{xy}', J_z', J_x' , and J_y' are set to 0.0, J', J', J_{xy}' , and J_{xy}' as defaults.)

Description : Spin-coupling constants between second nearest neighbor sites (See Fig. 4.1) are specified with these parameter. They are set as J, J_x, J_y, J_z , and J_{xy} are set.

- $J_0, J_1, J_2, J_{x0}, J_{y0}, J_{z0}, J_{x1}, J_{y1}, J_{z1}, J_{x2}, J_{y2}, J_{z2}, J_{xy0}, J_{xy1}, J_{xy2}$

Type : Real (J as default for J_0, J_1, J_2 . J_{xy} as defaults for $J_{xy0}, J_{xy1}, J_{xy2}$; J_x as defaults for J_{x0}, J_{x1}, J_{x2} ; J_y as defaults for J_{y0}, J_{y1}, J_{y2} ; J_z as defaults for J_{z0}, J_{z1}, J_{z2} .)

Description : Spin-coupling constants between nearest neighbor sites in the anisotropic honeycomb lattice (See Fig. 4.2) are specified with these parameter.

4.1.6 Parameters for the Kondo model

- μ

Type : Real (0.0 as a default)

Description : The chemical potential μ (including the site potential) is specified with this parameter.

- t

Type : Real (1.0 as a default)

Description : The nearest neighbor hopping t (See Fig. 4.1) is specified with this parameter.

- t_0, t_1, t_2

Type : Real (t as defaults)

Description : The nearest neighbor hopping in the anisotropic honeycomb lattice (See Fig. 4.2) is specified with this parameter.

- J

Type : Real(0.0 as a default)

Description : The spin-coupling constant between the valence and the local electrons is specified with this parameter.

4.1.7 Parameters for the numerical condition

- **Lanczos_max**

Type : Positive integer (2000 as a default)

Description : Upper limit of the Lanczos step is specified with this parameter.

- **initial_iv**

Type : Positive integer (1 as a default)

Description : The non-zero components of an initial vector is specified with this parameter. For grand canonical ensemble, the random vector is used as initial vector.

- **nvec**

Type : Positive integer (1 as a default)

Description : We specify the number of getting eigenvalues from the ground energy by Lanczos method.

When `nvec=2`, we obtain the ground-state energy and energy of the first-excited state.

- **exct**

Type : Positive integer (1 as a default)

Description : We specify the number of getting eigenvectors from the ground energy by Lanczos method.

When `exct=2`, we obtain the eigenvector of the first-excited state.

Note: the following condition must be satisfied: `nvec >= exct`.

- **LanczosEps**

Type : Positive Integer (14 as a default)

Description : The convergence criteria for the Lanczos method is specified with this parameter. If the difference between the old and the new target eigenvalue fall below $10^{-\text{LanczosEps}}$, the Lanczos step will finish.

- **LancczosTarget**

Type : Positive integer (2 as a default)

Description : We specify the target eigenenergy for the convergence criteria. If this set to 1, target eigenenergy becomes the ground state.

- **LargeValue**

Type : Integer (The default value is written below.)

Description : (Only for TPQ) We use l as $l - \hat{H}/N_s$ in the TPQ calculation. Usually, the largest eigenvalue of Hamiltonian is used as l . Thus, we take the default value of l for each models is as follows:

- Hubbard model [Eqn. (4.1)]

The canonical ensemble

$$l = |\mu| \frac{N_{\text{elec}}}{N_{\text{site}}} + 2z|t| + 2z'|t'| + |U| + 2z|V| + 2z'|V'| \quad (4.4)$$

The grand canonical ensemble

$$l = 2|\mu| + 2z|t| + 2z'|t'| + |U| + 2z|V| + 2z'|V'| \quad (4.5)$$

- Kitaev-Heisenberg model [Eqn. (4.2)]

The canonical ensemble

$$l = \frac{1}{2}|h| + \frac{1}{2}|D| + \frac{1}{4}|\Gamma| + \frac{z}{8}(|J_x| + |J_y| + |J_z|) + \frac{z'}{8}(|J'_x| + |J'_y| + |J'_z|) \quad (4.6)$$

The grand canonical ensemble

$$l = \frac{|S_z^{\text{tot}}|}{N_{\text{site}}}|h| + \frac{1}{2}|D| + \frac{1}{4}|\Gamma| + \frac{z}{8}(|J_x| + |J_y| + |J_z|) + \frac{z'}{8}(|J'_x| + |J'_y| + |J'_z|) \quad (4.7)$$

- Kondo lattice model [Eqn. (4.3)]

The canonical ensemble

$$l = |\mu| \frac{N_{\text{elec}}}{N_{\text{site}}} + 2z|t| + \frac{1}{4}|J| \quad (4.8)$$

The grand canonical ensemble

$$l = 2|\mu| + 2z|t| + \frac{1}{4}|J| \quad (4.9)$$

- NumAve

Type : Positive integer (5 as a default)

Description : (Only for the TPQ) The number of independent runs for the TPQ method is specified with this parameter.

- ExpecInterval

Type : Positive integer (20 as a default)

Description : (Only for the TPQ) We specify the interval steps of calculating correlation functions in TPQ method.

Note: The small interval increases the time cost of calculations.

4.2 Input files for *Expert* mode

In this section, details of input files for expert mode are explained. Input files are categorized by the following four parts.

(1) **List:** This file is a list of input file names with keywords. Each keywords is fixed, but file names are free to be determined.

(2) **Basic parameters:** The following input files give basic parameters. The kinds of input files are determined by keywords.

CalcMod: Set the parameters for calculation modes.

ModPara: Set the parameters for basic parameters such as site number, electron number, Lanczos step *etc.*

LocSpin: Set the location of local spin (only used in Kondo model).

(3) **Hamiltonian:** Hamiltonian for $\mathcal{H}\Phi$ is denoted by the format of interactions for electron system. The kinds of interactions are determined by the following keywords.

Trans: The one body part, $c_{i\sigma_1}^\dagger c_{j\sigma_2}$.

InterAll: The general two body interactions, $c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4}$.

We can set interactions which are often used by the following keywords.

CoulombIntra: On-site Coulomb interactions, $n_{i\uparrow}n_{i\downarrow}$ ($n_{i\sigma} = c_{i\sigma}^\dagger c_{i\sigma}$).

CoulombInter: Off-site Coulomb interactions, $n_i n_j$ ($n_i = n_{i\uparrow} + n_{i\downarrow}$).

Hund: Hund couplings, $n_{i\uparrow}n_{j\uparrow} + n_{i\downarrow}n_{j\downarrow}$.

PairHop: Pair hopping couplings, $c_{i\uparrow}^\dagger c_{j\uparrow} c_{i\downarrow}^\dagger c_{j\downarrow}$.

Exchange: Exchange couplings, $c_{i\uparrow}^\dagger c_{j\uparrow} c_{j\downarrow}^\dagger c_{i\downarrow}$.

Ising: Ising interactions, $S_i^z S_j^z$.

PairLift: PairLift couplings, $c_{i\uparrow}^\dagger c_{i\downarrow} c_{j\uparrow}^\dagger c_{j\downarrow}$.

(4) **Output:** Targets for output is determined.

OneBodyG : One-body green functions, $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} \rangle$.

TwoBodyG : Two-body green functions, $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4} \rangle$.

4.2.1 List file for Input files

. This file determines input filenames which are correlated with keywords. File format is shown as follows.

```
CalcMod  calcmdef.def
ModPara  modpara.def
LocSpin  zlocspn.def
Trans    ztransfer.def
InterAll zinterall.def
OneBodyG zcisajs.def
TwoBodyG zcisajsktaltdc.def
```

File format

[string01] [string02]

Parameters

- [string01]

Type : string-type

Description : Select a word from keywords.

- [string02]

Type : string-type

Description : An input filename which is correlated with keywords.

Use rules

- After setting keywords at [string 01], half-width state is needed for writing a filename. You can set the filename freely.
- Keywords for input files are shown in Table4.1.
- Essential keywords are “CalcMod”, “ModPara” and “LocSpin”.
- Keywords can be set in random order.
- If keywords or filenames are incorrect, the program is terminated.
- When the head of line is “#”, the line is skipped.

Keywords	Details for corresponding files
CalcMod	Parameters for modes of calculation.
ModPara	Parameters for calculation.
LocSpin	Configurations of the local spins for Hamiltonian.
Trans	Transfer and chemical potential for Hamiltonian.
InterAll	Two-body interactions for Hamiltonian.
CoulombIntra	CoulombIntra interactions.
CoulombInter	CoulombInter interactions.
Hund	Hund couplings.
PairHop	Pair hopping couplings.
Exchange	Exchange couplings.
Ising	Ising interactions.
PairLift	Pair lift couplings.
OneBodyG	Output components for Green functions $\langle c_{i\sigma}^\dagger c_{j\sigma} \rangle$
TwoBodyG	Output components for Correlation functions $\langle c_{i\sigma}^\dagger c_{j\sigma} c_{k\tau}^\dagger c_{l\tau} \rangle$

Table 4.1: List of the definition files.

4.2.2 CalcMod file

This file determines parameters for calculation method, model and output mode. File format is shown as follows.

```
CalcType    0
CalcModel   2
OutputMode   1
```

File format

[string01] [int01]

Parameters

- [string01]

Type : string-type

Description : Select a word from keywords.

- [int01]

Type : int-type

Description : A parameter which is correlated with a keyword.

Use rules

- After setting keywords at [string 01], a half-width blank is needed for setting a parameter.
- Keywords can be set in random order.
- If keywords or filenames are incorrect, the program is terminated.
- The following keywords, “CalcType” and “CalcModel” are essential.
- When the head of line is “#”, the line is skipped.

Keywords and parameters

Parameters correlated with keywords are shown as follows.

- **CalcType**

Type : int-type

Description : Select the method for calculation from the following list:

- 0: Lanczos method,
- 1: Analysis of the physical properties by using TPQ,
- 2: Full diagonalization method.

- **CalcModel**

Type : int-type

Description : Select the model from the following list:

- 0: fermion Hubbard model (Canonical ensemble: conservation of particles and the component of S_z)
- 1: Spin model (Canonical ensemble: conservation of the component of S_z)
- 2: Kondo lattice model (Canonical ensemble: conservation of particles and the component of S_z)
- 3: fermion Hubbard model (Grand canonical ensemble)
- 4: Spin model (Grand canonical ensemble)
- 5: Kondo lattice model (Grand canonical ensemble)

- **Outputmode**

Type : int-type (default value: 0)

Description : Select the output mode from the following list:

- 0: Output of Green’s function. The components are set by the OneBodyG and TwoBodyG input files.
- 1: Output of charge correlation function, spin correlation function and Green’s function (not supported in ver.0.1). The components of Green’s function are set by the OneBodyG and TwoBodyG input files.

4.2.3 ModPara file

This file determines parameters for calculation. File format is shown as follows.

```

-----
Model_Parameters    0
-----
VMC_Cal_Parameters
-----
CDataFileHead    zvo
CParaFileHead    zqp
-----
Nsite             16
Nup               8
Ndown            8
Lanczos_max      1000
initial_iv       12
nvec             1
exct             1
LanczosEps       14
LanczosTarget    2
LargeValue       12
NumAve           5
ExpecInterval    20

```

File format

- Lines 1-4: Header
- Line 6: [string01] [string02]
- Lines 7-8: Header
- Lines 9- : [string01] [int01]

Parameters

- [string01]
Type : string-type
Description : Select a word from keywords.
- [string02]
Type : string-type (blank parameter not allowed)
Description : Set a header for output files.

- [int01]

Type : int-type (blank parameter not allowed)

Description : A parameter which is correlated with a keyword.

Use rules

- From Line 9: After setting keywords at [string 01], a half-width blank is needed for setting a parameter.
- All Parameters are needed and the order for parameters is fixed.

Keywords and parameters

- CDataFileHead

Type : string-type (blank parameter not allowed)

Description : A header for output files. For example, the output filename for one body Green's function becomes "**xxx_Lanczos_cisajs.dat**" (xxx are characters set by CDataFileHead).

- Nsite

Type : int-type (Positive integer)

Description : The number of sites.

- Nup

Type : int-type (Positive integer)

Description : The number of up spin (not used in grand canonical ensemble).

- Ndown

Type : int-type (Positive integer)

Description : The number of down spin (not used in grand canonical ensemble).

- Lanczos_max

Type : int-type (Positive integer)

Description : The number of Lanczos steps in calculation. When the convergence within the specified accuracy is satisfied, the calculation is finished before a step becomes **Lanczos_max**.

- initial_iv

Type : int-type

Description : An integer for setting non-zero components of an initial vector. For grand canonical ensemble, the random number seed is given for getting initial vector including a lot states.

- **nvec**

Type : int-type (Positive integer)

Description : An integer for setting the number of getting eigenvalues from the ground energy by Lanczos method.

- **exct**

Type : int-type (Positive integer)

Description : An integer for setting the number of getting eigenvectors from the ground energy by Lanczos method.

Note: the following condition must be satisfied **nvec** \geq **exct**.

- **LanczosEps**

Type : int-type (Positive integer)

Description : An integer for judging a convergence of Lanczos method. The convergence is judged by satisfying the condition that the relative error between an eigenvalue and an eigenvalue at the Lanczos step of the one step before becomes less than $10^{-\text{LanczosEps}}$.

- **LanczosTarget**

Type : int-type (Positive integer)

Description : An integer giving the target of eigenvalue for judging the convergence of Lanczos method. For example, the target becomes a ground state when **LanczosTarget** is equal to one, and a 1st excited state when **LanczosTarget** is equal to two.

- **LargeValue**

Type : int-type

Description : (Only use for TPQ method) An integer giving l of $l - \hat{H}/N_s$ used in TPQ method.

- **NumAve**

Type : int-type

Description : (Only use for TPQ method) An integer giving the number of independent runs for TPQ method.

- **ExpecInterval**

Type : int-type

Description : (Only use for TPQ method) An integer giving the interval steps of calculating correlation functions in TPQ method.

Note: The small interval increases the time cost of calculations.

4.2.4 LocSpin file

This file determines sites with localized spins. File format is shown as follows.

```

=====
NlocalSpin      6
=====
=====i_0LocSpn_1IteElc =====
=====
    0      1
    1      0
    2      1
    3      0
    4      1
    5      0
    6      1
    7      0
    8      1
    9      0
   10      1
   11      0

```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of localized spins. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of localized spins.
- [int02]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}] < N_{\text{site}}$).

- [int03]

Type : int-type (blank parameter not allowed)

Description : An integer for selecting an electron state whether localized spin or itinerant electron states:

0: localized spin state,

1: Itinerant electron state.

Use rules

- Headers cannot be omitted.
- A program is terminated, when [int01] is different from the total number of localized spins indicated by [int03].
- A program is terminated, when [int02] is different from the total number of sites.
- A program is terminated under the condition $[\text{int02}] < 0$ or $\text{Nsite} \leq [\text{int02}]$.

4.2.5 Trans file

This file determines values of transfer integrals $t_{ij\sigma_1\sigma_2}$,

$$H+ = - \sum_{ij\sigma_1\sigma_2} t_{ij\sigma_1\sigma_2} c_{i\sigma_1}^\dagger c_{j\sigma_2}. \quad (4.10)$$

An example of file format is shown as follows.

```
=====
NTransfer      24
=====
=====i_j_s_tijs=====
=====
    0      0      2      0  1.000000  0.000000
    2      0      0      0  1.000000  0.000000
    0      1      2      1  1.000000  0.000000
    2      1      0      1  1.000000  0.000000
    2      0      4      0  1.000000  0.000000
    4      0      2      0  1.000000  0.000000
    2      1      4      1  1.000000  0.000000
    4      1      2      1  1.000000  0.000000
    4      0      6      0  1.000000  0.000000
    6      0      4      0  1.000000  0.000000
    4      1      6      1  1.000000  0.000000
    6      1      4      1  1.000000  0.000000
    6      0      8      0  1.000000  0.000000
    8      0      6      0  1.000000  0.000000
...

```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [int04] [int05] [double01] [double02]

Parameters

- [string01]

Type : string-type (blank parameter not allowed)

Description : A keyword for total number of transfer integrals. You can freely give a name of the keyword.

- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of transfer integrals.
- [int02], [int04]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int04}] < \text{Nsite}$).
- [int03], [int05]
Type : int-type (blank parameter not allowed)
Description : An integer giving a spin index,
0: up-spin,
1: down-spin.
- [double01]
Type : double-type (blank parameter not allowed)
Description : A value for a real part of $t_{ij\sigma_1\sigma_2}$.
- [double02]
Type : double-type (blank parameter not allowed)
Description : A value for an imaginary part of $t_{ij\sigma_1\sigma_2}$.

Use rules

- Headers cannot be omitted.
- Since Hamiltonian must be Hermitian, the following relation must be satisfied, $t_{ij\sigma_1\sigma_2} = t_{ji\sigma_2\sigma_1}^\dagger$. A program is terminated when the above relation is broken.
- A program is terminated, when components of on-site interactions are double counted.
- A program is terminated, when [int01] is different from the total number of transfer integrals defined in this file.
- A program is terminated, when [int02]-[int05] are out of range from the defined values.

4.2.6 InterAll file

This file determines values of generalized two body interactions integrals $I_{ijkl\sigma_1\sigma_2\sigma_3\sigma_4}$,

$$H+ = \sum_{i,j,k,l} \sum_{\sigma_1,\sigma_2,\sigma_3,\sigma_4} I_{ijkl\sigma_1\sigma_2\sigma_3\sigma_4} c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4}. \quad (4.11)$$

An example of file format is shown as follows.

```
=====
NInterAll      36
=====
=====zInterAll=====
=====
0   0   0   1   1   1   1   0   0.50  0.0
0   1   0   0   1   0   1   1   0.50  0.0
0   0   0   0   1   0   1   0   0.25  0.0
0   0   0   0   1   1   1   1  -0.25  0.0
0   1   0   1   1   0   1   0  -0.25  0.0
0   1   0   1   1   1   1   1   0.25  0.0
2   0   2   1   3   1   3   0   0.50  0.0
2   1   2   0   3   0   3   1   0.50  0.0
2   0   2   0   3   0   3   0   0.25  0.0
2   0   2   0   3   1   3   1  -0.25  0.0
2   1   2   1   3   0   3   0  -0.25  0.0
2   1   2   1   3   1   3   1   0.25  0.0
4   0   4   1   5   1   5   0   0.50  0.0
4   1   4   0   5   0   5   1   0.50  0.0
4   0   4   0   5   0   5   0   0.25  0.0
4   0   4   0   5   1   5   1  -0.25  0.0
4   1   4   1   5   0   5   0  -0.25  0.0
4   1   4   1   5   1   5   1   0.25  0.0
...
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [int04] [int05] [int06] [int07] [int08] [int09] [double01] [double02]

Parameters

- [string01]

Type : string-type (blank parameter not allowed)

Description : A keyword for total number of generalized two body interactions. You can freely give a name of the keyword.

- [int01]

Type : int-type (blank parameter not allowed)

Description : An integer giving total number of generalized two body interactions.

- [int02], [int04], [int06], [int08]

Type : int-type (blank parameter not allowed)

Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int04}], [\text{int06}], [\text{int08}] < \text{Nsite}$).

- [int03], [int05], [int07], [int09]

Type : int-type (blank parameter not allowed)

Description : An integer giving a spin index,
0: up-spin,
1: down-spin.

- [double01]

Type : double-type (blank parameter not allowed)

Description : A value for a real part of $I_{ijkl\sigma_1\sigma_2\sigma_3\sigma_4}$.

- [double02]

Type : double-type (blank parameter not allowed)

Description : A value for an imaginary part of $I_{ijkl\sigma_1\sigma_2\sigma_3\sigma_4}$.

Use rules

- Headers cannot be omitted.
- Since Hamiltonian must be Hermitian, the following relation must be satisfied, $I_{ijkl\sigma_1\sigma_2\sigma_3\sigma_4} = I_{lkji\sigma_4\sigma_3\sigma_2\sigma_1}^\dagger$. The relation $I_{ijkl\sigma_1\sigma_2\sigma_3\sigma_4} = I_{jilk\sigma_2\sigma_1\sigma_3\sigma_4}^\dagger$ is also allowed. A program is terminated when the above relations are broken.
- A program is terminated, when components of on-site interactions are double counted.
- A program is terminated, when [int01] is different from the total number of generalized two body interactions defined in this file.

- A program is terminated, when [int02]-[int09] are out of range from the defined values.

4.2.7 CoulombIntra file

This file determines values of on-site interactions U_i ,

$$H+ = \sum_i U_i n_{i\uparrow} n_{i\downarrow}. \quad (4.12)$$

An example of file format is shown as follows.

```
=====
NCoulombIntra 6
=====
=====i_0LocSpn_1IteElc =====
=====
  0  4.000000
  1  4.000000
  2  4.000000
  3  4.000000
  4  4.000000
  5  4.000000
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [double01]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of on-site interactions. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of on-site interactions.
- [int02]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}] < \text{Nsite}$).

- [double01]

Type : double-type (blank parameter not allowed)

Description : A value for U_i .

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of on-site interactions are double counted.
- A program is terminated, when [int01] is different from the total number of on-site interactions defined in this file.
- A program is terminated, when [int02] is out of range from the defined values.

4.2.8 CoulombInter file

This file determines values of off-site interactions V_{ij} ,

$$H+ = \sum_{i,j} V_{ij} n_i n_j. \quad (4.13)$$

An example of file format is shown as follows.

```
=====
NCoulombInter 6
=====
=====CoulombInter =====
=====
  0      1  1.0000
  1      2  1.0000
  2      3  1.0000
  3      4  1.0000
  4      5  1.0000
  5      0  1.0000
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [double01]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of off-site interactions. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of off-site interactions.
- [int02], [int03]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [int02], [int03] < N_{site}$).

- [double01]

Type : double-type (blank parameter not allowed)

Description : A value for V_{ij} .

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of off-site interactions are double counted.
- A program is terminated, when [int01] is different from the total number of off-site interactions defined in this file.
- A program is terminated, when either [int02] or [int03] are out of range from the defined values.

4.2.9 Hund file

This file determines values of Hund couplings J_{ij}^{Hund} ,

$$H+ = - \sum_{i,j} J_{ij}^{\text{Hund}} (n_{i\uparrow} n_{j\uparrow} + n_{i\downarrow} n_{j\downarrow}). \quad (4.14)$$

An example of file format is shown as follows.

```
=====
NHund 6
=====
=====Hund =====
=====
  0      1 -0.250000
  1      2 -0.250000
  2      3 -0.250000
  3      4 -0.250000
  4      5 -0.250000
  5      0 -0.250000
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [double01]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of Hund couplings. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of Hund couplings.
- [int02], [int03]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int03}] < \text{Nsite}$).

- [double01]

Type : double-type (blank parameter not allowed)

Description : A value for J_{ij}^{Hund} .

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of Hund couplings are double counted.
- A program is terminated, when [int01] is different from the total number of Hund couplings defined in this file.
- A program is terminated, when either [int02] or [int03] are out of range from the defined values.

4.2.10 PairHop file

This file determines values of PairHop couplings J_{ij}^{Pair} ,

$$H+ = \sum_{i,j} J_{ij}^{\text{Pair}} c_{i\uparrow}^\dagger c_{j\uparrow} c_{i\downarrow}^\dagger c_{j\downarrow}. \quad (4.15)$$

An example of file format is shown as follows.

```
=====
NPairhop 6
=====
=====Pairhop =====
=====
  0      1  0.50000
  1      2  0.50000
  2      3  0.50000
  3      4  0.50000
  4      5  0.50000
  5      0  0.50000
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [double01]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of PairHop couplings. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of PairHop couplings.
- [int02], [int03]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int03}] < \text{Nsite}$).

- [double01]

Type : double-type (blank parameter not allowed)

Description : A value for J_{ij}^{Pair} .

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of PairHop couplings are double counted.
- A program is terminated, when [int01] is different from the total number of PairHop couplings defined in this file.
- A program is terminated, when either [int02] or [int03] are out of range from the defined values.

4.2.11 Exchange file

This file determines values of Exchange couplings J_{ij}^{Ex} . For fermion electronic system, exchange terms are given as

$$H+ = \sum_{i,j} J_{ij}^{\text{Ex}} (c_{i\uparrow}^\dagger c_{j\uparrow} c_{j\downarrow}^\dagger c_{i\downarrow} + c_{i\downarrow}^\dagger c_{j\downarrow} c_{j\uparrow}^\dagger c_{i\uparrow}). \quad (4.16)$$

While for Spin system, they are given as

$$H+ = \sum_{i,j} J_{ij}^{\text{Ex}} (S_i^+ S_j^- + S_i^- S_j^+). \quad (4.17)$$

We note that $(S_i^+ S_j^- + S_i^- S_j^+)$ in Spin system is written by the operators for electrons as $-(c_{i\uparrow}^\dagger c_{j\uparrow} c_{j\downarrow}^\dagger c_{i\downarrow} + c_{i\downarrow}^\dagger c_{j\downarrow} c_{j\uparrow}^\dagger c_{i\uparrow})$. An example of file format is shown as follows.

```
=====
NExchange 6
=====
=====Exchange =====
=====
  0      1  0.50000
  1      2  0.50000
  2      3  0.50000
  3      4  0.50000
  4      5  0.50000
  5      0  0.50000
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [double01]

Parameters

- [string01]

Type : string-type (blank parameter not allowed)

Description : A keyword for total number of Exchange couplings. You can freely give a name of the keyword.

- [int01]

Type : int-type (blank parameter not allowed)

Description : An integer giving total number of Exchange couplings.

- [int02], [int03]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int03}] < \text{Nsite}$).
- [double01]
Type : double-type (blank parameter not allowed)
Description : A value for J_{ij}^{Ex} .

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of Exchange couplings are double counted.
- A program is terminated, when [int01] is different from the total number of Exchange couplings defined in this file.
- A program is terminated, when either [int02] or [int03] are out of range from the defined values.

4.2.12 Ising file

This file determines values of Ising interactions J_{ij}^z . For fermion electronic system, Ising terms are given as

$$H+ = \sum_{i,j} J_{ij}^z (n_{i\uparrow} - n_{i\downarrow})(n_{j\uparrow} - n_{j\downarrow}). \quad (4.18)$$

For Spin system, they are given as

$$H+ = \sum_{i,j} J_{ij}^z S_i^z S_j^z. \quad (4.19)$$

An example of file format is shown as follows.

```
=====
NIsing 6
=====
=====Ising =====
=====
  0      1  0.50000
  1      2  0.50000
  2      3  0.50000
  3      4  0.50000
  4      5  0.50000
  5      0  0.50000
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [double01]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of Ising interactions. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of Ising interactions.

- [int02], [int03]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int03}] < \text{Nsite}$).
- [double01]
Type : double-type (blank parameter not allowed)
Description : A value for J_{ij}^z .

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of Ising interactions are double counted.
- A program is terminated, when [int01] is different from the total number of Ising interactions defined in this file.
- A program is terminated, when either [int02] or [int03] are out of range from the defined values.

4.2.13 PairLift file

This file determines values of PairLift couplings J_{ij}^{PairLift} ,

$$H+ = \sum_{i,j} J_{ij}^{\text{PairLift}} (c_{i\uparrow}^\dagger c_{i\downarrow} c_{j\uparrow}^\dagger c_{j\downarrow} + c_{i\downarrow}^\dagger c_{i\uparrow} c_{j\downarrow}^\dagger c_{j\uparrow}). \quad (4.20)$$

An example of file format is shown as follows.

```
=====
NPairLift 6
=====
=====NPairLift =====
=====
  0      1  0.50000
  1      2  0.50000
  2      3  0.50000
  3      4  0.50000
  4      5  0.50000
  5      0  0.50000
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [double01]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of PairLift couplings. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of PairLift couplings.
- [int02], [int03]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int03}] < \text{Nsite}$).

- [double01]

Type : double-type (blank parameter not allowed)

Description : A value for J_{ij}^{PairLift} .

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of PairLift couplings are double counted.
- A program is terminated, when [int01] is different from the total number of PairLift couplings defined in this file.
- A program is terminated, when either [int02] or [int03] are out of range from the defined values.

4.2.14 OneBodyG file

This file determines the target components of one-body Green's function $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} \rangle$. An example of file format is shown as follows.

```
=====
NCisAjs          24
=====
===== Green functions =====
=====
  0      0      0      0
  0      1      0      1
  1      0      1      0
  1      1      1      1
  2      0      2      0
  2      1      2      1
  3      0      3      0
  3      1      3      1
  4      0      4      0
  4      1      4      1
  5      0      5      0
  5      1      5      1
  6      0      6      0
  6      1      6      1
  7      0      7      0
  7      1      7      1
  8      0      8      0
  8      1      8      1
  9      0      9      0
  9      1      9      1
 10      0     10      0
 10      1     10      1
 11      0     11      0
 11      1     11      1
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [int04] [int05]

Parameters

- [string01]
Type : string-type (blank parameter not allowed)
Description : A keyword for total number of one-body Green's functions. You can freely give a name of the keyword.
- [int01]
Type : int-type (blank parameter not allowed)
Description : An integer giving total number of one-body Green's functions.
- [int02], [int04]
Type : int-type (blank parameter not allowed)
Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int04}] < \text{Nsite}$).
- [int03], [int05]
Type : int-type (blank parameter not allowed)
Description : An integer giving a spin index,
0: up-spin,
1: down-spin.

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of one-body Green's functions are double counted.
- A program is terminated, when [int01] is different from the total number of one-body Green's functions defined in this file.
- A program is terminated, when [int02]-[int05] are out of range from the defined values.

4.2.15 TwoBodyG file

This file determines the target components of two-body Green's function $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4} \rangle$. An example of file format is shown as follows.

```
=====
NCisAjsCktAltDC          576
=====
===== Green functions for Sq AND Nq =====
=====
  0    0    0    0    0    0    0    0
  0    0    0    0    0    1    0    1
  0    0    0    0    1    0    1    0
  0    0    0    0    1    1    1    1
  0    0    0    0    2    0    2    0
  0    0    0    0    2    1    2    1
  0    0    0    0    3    0    3    0
  0    0    0    0    3    1    3    1
  0    0    0    0    4    0    4    0
  0    0    0    0    4    1    4    1
  0    0    0    0    5    0    5    0
  0    0    0    0    5    1    5    1
  0    0    0    0    6    0    6    0
  0    0    0    0    6    1    6    1
  0    0    0    0    7    0    7    0
  0    0    0    0    7    1    7    1
  0    0    0    0    8    0    8    0
  0    0    0    0    8    1    8    1
  0    0    0    0    9    0    9    0
  0    0    0    0    9    1    9    1
  0    0    0    0   10    0   10    0
  0    0    0    0   10    1   10    1
  0    0    0    0   11    0   11    0
  0    0    0    0   11    1   11    1
  0    1    0    1    0    0    0    0
  ...
```

File format

- Line 1: Header
- Line 2: [string01] [int01]
- Lines 3-5: Header
- Lines 6-: [int02] [int03] [int04] [int05] [int06] [int07] [int08] [int09]

Parameters

- [string01]

Type : string-type (blank parameter not allowed)

Description : A keyword for total number of two-body Green's functions. You can freely give a name of the keyword.

- [int01]

Type : int-type (blank parameter not allowed)

Description : An integer giving total number of two-body Green's functions.

- [int02], [int04],[int06], [int08]

Type : int-type (blank parameter not allowed)

Description : An integer giving a site index ($0 \leq [\text{int02}], [\text{int04}], [\text{int06}], [\text{int08}] < N_{\text{site}}$).

- [int03], [int05],[int07], [int09]

Type : int-type (blank parameter not allowed)

Description : An integer giving a spin index,
0: up-spin,
1: down-spin.

Use rules

- Headers cannot be omitted.
- A program is terminated, when components of two-body Green's functions are double counted.
- A program is terminated, when [int01] is different from the total number of two-body Green's functions defined in this file.
- A program is terminated, when [int02]-[int09] are out of range from the defined values.

4.3 Output files

In this section, details of output files for expert mode are explained.

4.3.1 CHECK_Chemi.dat

This file is outputted to check the input of chemical potential $\mu_{i\sigma}$,

$$H+ = \sum_{i,\sigma} \mu_{i\sigma} c_{i\sigma}^\dagger c_{i\sigma}. \quad (4.21)$$

An example of file format is shown as follows.

```
i=0 spin=0 isite1=1 tmp_V=0.000000
i=1 spin=0 isite1=2 tmp_V=0.000000
i=2 spin=0 isite1=3 tmp_V=0.000000
i=3 spin=0 isite1=4 tmp_V=0.000000
i=4 spin=0 isite1=5 tmp_V=0.000000
i=5 spin=0 isite1=6 tmp_V=0.000000
...
```

File format

- `i=[int01] spin=[int02] isite1=[int03] tmp_V=[double01]`

Parameters

- `[int01]`
Type : int-type
Description : A counted number of inputting terms.
- `[int02]`
Type : int-type
Description : An integer for showing a spin index of $\mu_{i\sigma}$,
0: up-spin,
1: down-spin.
- `[int03]`
Type : int-type
Description : An integer for showing a site index of $\mu_{i\sigma}$.
- `[double01]`
Type : double-type
Description : A value for $\mu_{i\sigma}$.

4.3.2 CHECK_InterAll.dat

This file is outputted to check the input of diagonal components of general two body interactions,

$$H+ = \sum_{i,j,\sigma} I_{ijj\sigma_1\sigma_1\sigma_2\sigma_2} c_{i\sigma_1}^\dagger c_{i\sigma_1} c_{i\sigma_2}^\dagger c_{i\sigma_2}. \quad (4.22)$$

An example of file format is shown as follows.

```
i=0 isite1=1 A_spin=0 isite2=2 B_spin=0 tmp_V=0.500000
i=1 isite1=1 A_spin=0 isite2=2 B_spin=1 tmp_V=-0.500000
i=2 isite1=1 A_spin=1 isite2=2 B_spin=0 tmp_V=-0.500000
i=3 isite1=1 A_spin=1 isite2=2 B_spin=1 tmp_V=0.500000
i=4 isite1=2 A_spin=0 isite2=3 B_spin=0 tmp_V=0.500000
i=5 isite1=2 A_spin=0 isite2=3 B_spin=1 tmp_V=-0.500000
...
```

File format

- `i=[int01] isite1=[int02] A_spin=[int03] isite2=[int04] B_spin=[int05] tmp_V=[double01]`

Parameters

- `[int01]`

Type : int-type

Description : A counted number of inputting terms.

- `[int02], [int04]`

Type : int-type

Description : An integer for showing a site index of $I_{ijj\sigma_1\sigma_1\sigma_2\sigma_2}$.
`[int02]` and `[int04]` correspond to i and j , respectively.

- `[int03], [int05]`

Type : int-type

Description : An integer for showing a spin index of $I_{ijj\sigma_1\sigma_1\sigma_2\sigma_2}$,
 0: up-spin,
 1: down-spin.
`[int03]` and `[int05]` correspond to σ_1 and σ_2 , respectively.

- `[double01]`

Type : double-type

Description : A value for $I_{ijj\sigma_1\sigma_1\sigma_2\sigma_2}$.

4.3.3 CHECK_CoulombIntra.dat

This file is outputted to check the input of on-site interactions U_i ,

$$H+ = \sum_i U_i n_{i\uparrow} n_{i\downarrow}. \quad (4.23)$$

An example of file format is shown as follows.

```
i=0 isite1=1 tmp_V=4.000000
i=1 isite1=2 tmp_V=4.000000
i=2 isite1=3 tmp_V=4.000000
i=3 isite1=4 tmp_V=4.000000
i=4 isite1=5 tmp_V=4.000000
i=5 isite1=6 tmp_V=4.000000
```

File format

- $i=[\text{int01}]$ $\text{isite1}=[\text{int02}]$ $\text{tmp_V}=[\text{double01}]$

Parameters

- $[\text{int01}]$
Type : int-type
Description : A counted number of inputting terms.
- $[\text{int02}]$
Type : int-type
Description : An integer for showing a site index of U_i .
- $[\text{double01}]$
Type : double-type
Description : A value for U_i .

4.3.4 CHECK_Hund.dat

This file is outputted to check the input of Hund couplings J_{ij}^{Hund} ,

$$H+ = - \sum_{i,j} J_{ij}^{\text{Hund}} (n_{i\uparrow} n_{j\uparrow} + n_{i\downarrow} n_{j\downarrow}). \quad (4.24)$$

An example of file format is shown as follows.

```
i=0 isite1=1 isite2=2 tmp_V=0.250000
i=1 isite1=2 isite2=3 tmp_V=0.250000
i=2 isite1=3 isite2=4 tmp_V=0.250000
i=3 isite1=4 isite2=5 tmp_V=0.250000
i=4 isite1=5 isite2=6 tmp_V=0.250000
i=5 isite1=6 isite2=1 tmp_V=0.250000
```

File format

- $i=[\text{int01}]$ $\text{isite1}=[\text{int02}]$ $\text{isite2}=[\text{int03}]$ $\text{tmp_V}=[\text{double01}]$

Parameters

- $[\text{int01}]$

Type : int-type

Description : A counted number of inputting terms.

- $[\text{int02}], [\text{int03}]$

Type : int-type

Description : An integer for showing a site index of J_{ij}^{Hund} .
 $[\text{int02}]$ and $[\text{int03}]$ correspond to i and j , respectively.

- $[\text{double01}]$

Type : double-type

Description : A value for J_{ij}^{Hund} .

4.3.5 CHECK_INTER_U.dat

This file is outputted to check the input of diagonal components of on-site interactions V_{ij} ,

$$H+ = \sum_i V_{ij} n_i n_j \quad (4.25)$$

An example of file format is shown as follows.

```
i=0 isite1=1 isite2=2 tmp_V=-0.125000
i=1 isite1=2 isite2=3 tmp_V=-0.125000
i=2 isite1=3 isite2=4 tmp_V=-0.125000
i=3 isite1=4 isite2=5 tmp_V=-0.125000
i=4 isite1=5 isite2=6 tmp_V=-0.125000
i=5 isite1=6 isite2=1 tmp_V=-0.125000
```

File format

- $i=[\text{int01}]$ $\text{isite1}=[\text{int02}]$ $\text{isite2}=[\text{int03}]$ $\text{tmp_V}=[\text{double01}]$

Parameters

- $[\text{int01}]$
Type : int-type
Description : A counted number of inputting terms.
- $[\text{int02}], [\text{int03}]$
Type : int-type
Description : An integer giving a site index of V_{ij} .
 $[\text{int02}]$ and $[\text{int03}]$ correspond to i and j , respectively.
- $[\text{double01}]$
Type : double-type
Description : A value for V_{ij} .

4.3.6 CHECK_Memory.dat

This file shows the size of memory using the calculation. An example of file format is shown as follows.

```
MAX DIMENSION idim_max=400
REQUIRED MEMORY max_mem=0.000019 GB
```

File format

- MAX DIMENSION idim_max=[int01]
- REQUIRED MEMORY max_mem =[double01] GB

Parameters

- [int01]

Type : int-type

Description : An integer to show total numbers of the Hilbert space under a calculation.

- [double01]

Type : double-type

Description : A size of memory to store the Hilbert space under a calculation (GB unit).

4.3.7 WarningOnTransfer.dat

This file shows the components double counted of transfer integrals. An example of file format is shown as follows.

```
double conuntings in transfers: i=0 j=2 spni 0 spnj 0
double conuntings in transfers: i=2 j=0 spni 0 spnj 0
double conuntings in transfers: i=0 j=2 spni 1 spnj 1
double conuntings in transfers: i=2 j=0 spni 1 spnj 1
```

File format

- double countings in transfers: i=[int01] j=[int02] spni [int03] spnj [int04]

Parameters

- [int01], [int02]

Type : int-type

Description : An integer of a site number where transfer integrals are double counted.

- [int03], [int04]

Type : int-type

Description : An integer of a spin index of a transfer integral,
0: up-spin,
1: down-spin.

4.3.8 TimeKeeper.dat

This file is outputted to show the calculation process information. An example of file format for Lanczos method is shown as follows.

```
diagonal calculation finishes: Wed Sep 16 22:58:49 2015
Lanczos Eigen Value start: Wed Sep 16 22:58:49 2015
1 th Lanczos step: Wed Sep 16 22:58:49 2015
...
122 th Lanczos step: Wed Sep 16 22:58:49 2015
Lanczos Eigenvalue finishes: Wed Sep 16 22:58:49 2015
Lanczos Eigenvector finishes: Wed Sep 16 22:58:49 2015
Lanczos expec energy finishes: Wed Sep 16 22:58:49 2015
CG Eigenvector finishes: Wed Sep 16 22:58:49 2015
CG expec energy finishes: Wed Sep 16 22:58:50 2015
CG expec_cisajs finishes: Wed Sep 16 22:58:50 2015
CG expec_cisajacktalt begins: Wed Sep 16 22:58:50 2015
```

File name

- `##_TimeKeeper.dat`

`##_` indicates a header defined by [string02] in a ModPara file.

4.3.9 sz_TimeKeeper.dat

This file is outputted to show the process information to obtain the Hilbert space needed for calculation . An example of file format is shown as follows.

```
initial sz : Wed Sep 16 22:58:49 2015
num_threads==4
omp parallel sz finishes: Wed Sep 16 22:58:49 2015
mid omp parallel sz : Wed Sep 16 22:58:49 2015
omp parallel sz finishes: Wed Sep 16 22:58:49 2015
```

File name

- `##_sz_TimeKeeper.dat`

`##_` indicates a header defined by [string02] in a ModPara file.

4.3.10 Time_CG_EigenVector.dat

(For Lanczos method) The process for calculating eigenvector by CG method is outputted. An example of file format is shown as follows.

```
allocate succeed !!!
b[4341]=1.000000 bnorm== 1.000000
i_itr=0 itr=5 0.0411202543 0.0000100000
...
i_itr=0 itr=155 0.00000000058 0.0000100000
CG OK:   t_itr=155
i_itr=0 itr=155 time=0.000000
fabs(fabs(xb)-1.0)=0.9955114473313577
b[4341]=0.004489 bnorm== 1.000000
i_itr=1 itr=5 13.0033983157 0.0000100000
...
CG OK:   t_itr=275
i_itr=1 itr=120 time=0.000000
fabs(fabs(xb)-1.0)=0.0000000000001295
number of iterations in inv1:i_itr=1 itr=120
t_itr=275 0.000000
```

File name

- ##_Time_CG_EigenVector.dat

indicates a header defined by [string02] in a ModPara file.

4.3.11 energy.dat

(For Lanczos method) The values of energy and doublon calculated by using eigenvector obtained by Lanczos or CG method are outputted. An example of file format is shown as follows.

```
Energy  -7.1043675920
Doublon 0.4164356536
```

File name

- `##_energy.dat`

`##_` indicates a header defined by `[string02]` in a ModPara file.

File format

- Line 1: Energy `[double01]`
- Line 2: Doublon `[double02]`

Parameters

- `[double01]`

Type : double-type

Description : The value of energy calculated by the eigenvetor obtained by Lanczos or CG method.

- `[double02]`

Type : double-type

Description : The value of doublon calculated by the eigenvetor obtained by Lanczos or CG method, $\frac{1}{N_s} \sum_i \langle n_{i\uparrow} n_{i\downarrow} \rangle$ (N_s is a total number of sites).

4.3.12 Lanczos_Step.dat

(For Lanczos method) This file is outputted to show the process information for calculating eigenvector by Lanczos method. An example of file format for Lanczos method is shown as follows.

```
stp=4 -4.7732163164 -1.7790936582 1.2246691944 4.4823068739
stp=6 -5.8159638812 -3.6807425834 -1.3738652472 0.9326262962
stp=8 -6.2772935672 -4.8650501184 -3.1096996066 -1.1940653342
...
stp=120 -7.1043675920 -7.0817672578 -7.0646589929 -7.0008766356
stp=122 -7.1043675920 -7.0817672578 -7.0646589929 -7.0008766356
```

File name

- ##_Lanczos_Step.dat

indicates a header defined by [string02] in a ModPara file.

File format

- stp= [int01] [double01] [double02] [double03] [double04]

Parameters

- [int01]

Type : int-type

Description : An integer showing Lanczos step.

- [double01], [double02], [double03], [double04]

Type : double-type

Description : The eigenvalue at the Lanczos step [int01].

[double01] is a ground energy, [double02], [double03] and [double04] are 1st, 2nd and 3rd excited energies, respectively.

4.3.13 Norm_rand.dat

(For TPQ method) This file is outputted to show the calculation process information for TPQ method. An example of file format is shown as follows.

```
# inv_temp, global_norm, global_1st_norm, step_i
0.017471 19.046586 11.288975 1
0.034863 19.089752 11.288975 2
...
31.999572 20.802362 11.288975 1997
32.015596 20.802362 11.288975 1998
32.031620 20.802362 11.288975 1999
```

File name

- Norm_rand???.dat

?? indicates a number of runs under calculation of TPQ method.

File format

- Line 1: Header
- Lines 2-: [double01] [double02] [double03] [int01]

Parameters

- [double01]
Type : double-type
Description : Inverse temperature $1/k_{\text{B}}T$.
- [double02]
Type : double-type
Description : A norm of a wave function before normalization given by $\langle \tilde{\psi}_k | \tilde{\psi}_k \rangle$, where $|\tilde{\psi}_k\rangle \equiv (l - \hat{H}/N_s)|\psi_{k-1}\rangle$.
- [double03]
Type : double-type
Description : A norm of an initial wave function before normalization given by $\langle \tilde{\psi}_0 | \tilde{\psi}_0 \rangle$, where $|\tilde{\psi}_0\rangle$ is an initial random vector.
- [int01]
Type : int-type
Description : A number of operations of $(l - \hat{H}/N_s)$ to an initial wave function, where l is **LargeValue** defined in ModPara file and N_s is a total number of sites.

4.3.14 SS_rand.dat

(For TPQ method) This file is outputted to show the calculation results for TPQ method. An example of file format is shown as follows.

```
# inv_tmp, energy, phys_var, phys_doublon, phys_num, step_i
0.017471  5.526334 45.390269 1.464589 6.000000 1
0.034863  5.266718 42.655559 1.434679 6.000000 2
...
31.999572 -4.814170 23.176231 0.590568 6.000000 1997
32.015596 -4.814170 23.176231 0.590568 6.000000 1998
32.031620 -4.814170 23.176231 0.590568 6.000000 1999
```

File name

- SS_rand???.dat

?? indicates a number of runs under calculation of TPQ method.

File format

- Line 1: Header
- Lines 2-: [double01] [double02] [double03] [double04] [double05] [int01]

Parameters

- [double01]
Type : double-type
Description : Inverse temperature $1/k_{\text{B}}T$.
- [double02]
Type : double-type
Description : The expected value of energy $\langle H \rangle$.
- [double03]
Type : double-type
Description : The expected value of square of Hamiltonian $\langle H^2 \rangle$.
- [double03]
Type : double-type
Description : The expected value of doublon, $\frac{1}{N_s} \sum_i \langle n_{i\uparrow} n_{i\downarrow} \rangle$ (N_s is a total number of sites).

- [double05]

Type : double-type

Description : A total number of particles $\langle \hat{n} \rangle$.

- [int01]

Type : int-type

Description : A number of operations of $(l - \hat{H}/N_s)$ to an initial wave function, where l is **LargeValue** defined in ModPara file and N_s is a total number of sites.

4.3.15 Eigenvalue.dat

(For FullDiag method) This file is outputted to show the energies calculated by FullDiag method. An example of file format is shown as follows.

```
0 -4.8141698096
1 -3.7968502453
2 -3.2462822372
...
397 13.9898305290
398 14.4896221034
399 14.8525199079
```

File format

- [int01] [double01]

Parameters

- [int01]

Type : int-type

Description : An index of eigenvalues. The index 0 is for an energy of a ground state and indexes are counted from the low order of energies.

- [double01]

Type : double-type

Description : The expected value of energy $\langle H \rangle$.

4.3.16 phys.dat

(For FullDiag method) This file is outputted to show the physical values calculated by FullDiag method. The datas are outputted in the low order of energies. An example of file format is shown as follows.

<H>	<N>	<Sz>	<S2>	<D>
-4.814170	0.000000	0.000000	-0.000000	0.590568
-3.796850	0.000000	0.000000	1.333333	0.423804
...				
14.489622	0.000000	0.000000	0.000000	2.550240
14.852520	0.000000	0.000000	0.000000	2.329157

File name

- Canonical ensemble: `##_phys_Nup_$$Ndown%%.dat`
- Grand canonical ensemble: `##_phys.dat`

##, \$\$ and %% indicate [string02], Nup and Ndown defined in a ModPara file, respectively.

File format

- Line 1: Header
- Lines 2-: [double01] [double02] [double03] [double04] [double05]

Parameters

- [double01]
Type : double-type
Description : The energy $\langle H \rangle$.
- [double02]
Type : double-type
Description : A total number of particles $\langle \hat{n} \rangle$.
- [double03]
Type : double-type
Description : The expected value of S_z , $\langle S_z \rangle$.
- [double04]
Type : double-type
Description : The expected value of S^2 , $\langle S^2 \rangle$.

- [double05]

Type : double-type

Description : The expected value of doublon, $\frac{1}{N_s} \sum_i \langle n_{i\uparrow} n_{i\downarrow} \rangle$ (N_s is a total number of sites).

4.3.17 cisajs.dat

This file is output files for one-body Green's function $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} \rangle$. The target components are set in the input file with the keyword "OneBodyG". An example of file format is shown as follows.

```

0    0    0    0 0.4452776740 0.0000000000
0    1    0    1 0.4452776740 0.0000000000
1    0    1    0 0.5000000000 0.0000000000
1    1    1    1 0.5000000000 0.0000000000
2    0    2    0 0.4452776740 0.0000000000
2    1    2    1 0.4452776740 0.0000000000
3    0    3    0 0.5000000000 0.0000000000
3    1    3    1 0.5000000000 0.0000000000
...
```

File name

- Lanczos method: `##_cisajs.dat`
- TPQ method: `##_cisajs_set??step%%.dat`
- Full diagonalization method: `##_cisajs_eigen&&.dat`

`##_`, `??`, `%%` and `&&` indicate [string02] in ModPara file, a number of runs under calculation in TPQ method, a number of steps in TPQ method and an index of eigenvalues, respectively.

File format

- [int01] [int02] [int03] [int04] [double01] [double02]

Parameters

- [int01], [int03]

Type : int-type

Description : An integer of the site number. [int01] and [int03] show the i and j site numbers, respectively.

- [int02], [int04]

Type : int-type

Description : An integer of the spin index,

0: up-spin,

1: down-spin.

[int02] and [int04] show σ_1 and σ_2 , respectively.

- [double01], [double02]

Type : double-type

Description : The value of $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} \rangle$.

[double01] and [double02] show the real and imaginary part of $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} \rangle$, respectively.

4.3.18 cisajscktalt.dat

This file is output files for Two body Green's function $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4} \rangle$. The target components are set in the input file with the keyword "TwoBodyG". An example of file format is shown as follows.

```

0    0    0    0    0    0    0    0 0.4452776740 0.0000000000
0    0    0    0    0    1    0    1 0.1843355815 0.0000000000
0    0    0    0    1    0    1    0 0.1812412105 0.0000000000
0    0    0    0    1    1    1    1 0.2640364635 0.0000000000
0    0    0    0    2    0    2    0 0.0279690007 0.0000000000
0    0    0    0    2    1    2    1 0.2009271524 0.0000000000
0    0    0    0    3    0    3    0 0.2512810778 0.0000000000
0    0    0    0    3    1    3    1 0.1939965962 0.0000000000
...
```

File name

- Lanczos method: ##_cisajscktalt.dat
- TPQ method: ##_cisajscktalt_set??step%%.dat
- Full diagonalization method: ##_cisajscktalt_eigen&&.dat

##, ??, %% and && indicate [string02] in ModPara file, a number of runs under calculation in TPQ method, a number of steps in TPQ method and an index of eigenvalues, respectively.

File format

- [int01] [int02] [int03] [int04] [int05] [int06] [int07] [int08] [double01] [double02]

Parameters

- [int01], [int03],[int05], [int07]

Type : int-type

Description : An integer of the site number. [int01], [int03], [int05] and [int07] show the i , j , k and l site numbers, respectively.

- [int02], [int04],[int06], [int08]

Type : int-type

Description : An integer of the spin index,

0: up-spin,

1: down-spin.

[int02], [int04], [int06] and [int08] show σ_1 , σ_2 , σ_3 and σ_4 , respectively.

- [double01], [double02]

Type : double-type

Description : The value of $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4} \rangle$.

[double01] and [double02] show the real and imaginary part of $\langle c_{i\sigma_1}^\dagger c_{j\sigma_2} c_{k\sigma_3}^\dagger c_{l\sigma_4} \rangle$, respectively.

4.4 Error messages

- ERROR ! Unsupported Keyword !

The program stops because unsupported keyword is specified.

- "ERROR ! Keyword *keyword* is duplicated !

The program stops because a parameter is specified twice.

- ERROR ! Unsupported Solver : *solver*

- ERROR ! Unsupported Model : *model*

- Sorry, this system is unsupported in the STANDARD MODE...

Please use the EXPART MODE, or write a NEW FUNCTION and post it us.

The program stops because unsupported parameter for method, model, or lattice is specified.

- ERROR ! $\text{abs}(2 * \text{Sz}) > \text{n site}$ in Hubbard model !
- ERROR ! $\text{Nelec} > 2 * \text{n site}$ in Hubbard model !
- ERROR ! $(\text{nelec} + 2 * \text{Sz}) \% 2 \neq 0$ in Hubbard model !
- ERROR ! $\text{nelec} \leq \text{n site} \ \&\& \ 2 * |\text{Sz}| > \text{nelec}$ in Hubbard model !
- ERROR ! $\text{nelec} > \text{n site} \ \&\& \ 2 * |\text{Sz}| > 2 * \text{n site} - \text{nelec}$ in Hubbard model !
- ERROR ! $\text{abs}(2 * \text{Sz}) > \text{n site}$ in Spin model !
- ERROR ! $(\text{n site} + 2 * \text{Sz}) \% 2 \neq 0$ in Spin model !
- ERROR ! $\text{abs}(2 * \text{Sz}) > \text{n site}$ in Hubbard model !
- ERROR ! $\text{Nelec_cond} / 2 + \text{Nelec_loc} > \text{n site}$ in Kondo model !
- ERROR ! $(\text{nelec_cond} + \text{nelec_loc} + 2 * \text{Sz}) \% 2 \neq 0$ in Kondo model !
- ERROR ! $\text{nelec_cond} \leq \text{n site} / 2 \ \&\& \ 2 * |\text{Sz}| > \text{nelec_cond} + \text{nelec_loc} \dots$
- ERROR ! $\text{nelec_cond} > \text{n site} / 2 \ \&\& \ \text{abs}(\text{Sz}2) > \text{n site} / 2 * 3 - \text{nelec} \dots$

In the calculation of the canonical ensemble, there are some irrelevant combinations of the number of electrons, the number of sites, and the total spin moment (the number of electrons is larger twice than the number of sites); If these situations are detected, the program will stop.

- Check ! *keyword* is SPECIFIED but will NOT be USED.

Please COMMENT-OUT this line

or check this input is REALLY APPROPRIATE for your purpose !

Because an unnecessary parameter is specified, the program suggests checking the input file. If that parameter is actually unnecessary, please delete or comment out this line.

- **ERROR ! *keyword* is NOT specified !**

The program stops because a prerequisite keyword is not specified.

- ***keyword* = *value* ##### DEFAULT VALUE IS USED #####**

This is not an error message. The program states that the default value is used because this keyword is not specified.

5

Algorithm

5.1 Lanczos method

5.1.1 Details of Lanczos method

Some parts of this section are based on the manual of titpack [7] and textbook by M. Sugihara and K. Murota [8](These references are written in Japanese).

In the Lanczos method, by successively operating the Hamiltonian to the initial vector, we obtain the accurate eigenvalues around the maximum and minimum eigenvalues and associated eigenvectors. Because we can perform Lanczos method by using only two vectors whose dimensions are the dimension of the total Hilbert space ^{*1}, Lanczos method is frequently used for the diagonalization of the large matrices. As we detail below, one additional vector is necessary for obtaining the eigenvector.

The principle of the Lanczos method is based on the power method. In the power method, by successively operating the Hamiltonian $\hat{\mathcal{H}}$ to the arbitrary vector \mathbf{x}_0 , we generate $\hat{\mathcal{H}}^n \mathbf{x}_0$. The obtained space $\mathcal{K}_{n+1}(\hat{\mathcal{H}}, \mathbf{x}_0) = \{\mathbf{x}_0, \hat{\mathcal{H}} \mathbf{x}_0, \dots, \hat{\mathcal{H}}^n \mathbf{x}_0\}$ is called Krylov subspace. Initial vector is represented by the superposition of the eigenvectors \mathbf{e}_i (corresponding eigenvalues are E_i) of $\hat{\mathcal{H}}$ as

$$\mathbf{x}_0 = \sum_i a_i \mathbf{e}_i. \quad (5.1)$$

Here, E_0 is maximum absolute values of the eigenvalues. We note that all the eigenvalues are real number because Hamiltonian is Hermite. By operating $\hat{\mathcal{H}}^n$ to the initial vector, we obtain the relation as

$$\hat{\mathcal{H}}^n \mathbf{x}_0 = E_0^n \left[a_0 \mathbf{e}_0 + \sum_{i \neq 0} \left(\frac{E_i}{E_0} \right)^n a_i \mathbf{e}_i \right]. \quad (5.2)$$

This relation indicates that the eigenvector of E_0 becomes dominant for sufficiently large n . In the Lanczos method, we obtain the eigenvalues and eigenvectors by performing the proper transformation for obtained Krylov subspace.

In the Lanczos method, we successively generate the normalized orthogonal basis $\mathbf{v}_0, \dots, \mathbf{v}_{n-1}$ from the Krylov subspace $\mathcal{K}_n(\hat{\mathcal{H}}, \mathbf{x}_0)$. We defines initial vector and

^{*1}In $\mathcal{H}\Phi$, to reduce the numerical cost, we use some additional vectors; vector for accumulating the real-space diagonal elements of the Hamiltonian, vector for specifying the given S_z space and given particle space. The dimension of these vectors is that of the Hilbert space.

associated components as $\mathbf{v}_0 = \mathbf{x}_0/|\mathbf{x}_0|$, $\beta_0 = 0$, $\mathbf{x}_{-1} = 0$. From this initial condition, we can obtain the normalized orthogonal basis as follows:

$$\alpha_k = (\hat{\mathcal{H}}\mathbf{v}_k, \mathbf{v}_k), \quad (5.3)$$

$$\mathbf{w} = \hat{\mathcal{H}}\mathbf{v}_k - \beta_k\mathbf{v}_{k-1} - \alpha_k\mathbf{v}_k, \quad (5.4)$$

$$\beta_{k+1} = |\mathbf{w}|, \quad (5.5)$$

$$\mathbf{v}_{k+1} = \frac{\mathbf{v}_k}{|\mathbf{v}_k|}. \quad (5.6)$$

From these definitions, it is obvious that α_k, β_k are real numbers.

In the subspace spanned by these normalized orthogonal basis, the Hamiltonian is transformed as

$$T_n = V_n^\dagger \hat{\mathcal{H}} V_n. \quad (5.7)$$

Here, V_n is matrix whose column vectors are $\mathbf{v}_i (i = 0, 1, \dots, n-1)$. T_n is tridiagonal matrix and its diagonal elements are α_i and subdiagonal elements are β_i . It is known that the eigenvalues of $\hat{\mathcal{H}}$ are well approximated by the eigenvalues of T_n for sufficiently large n . (We note that $V^\dagger V = I$, I is identity matrix). The original eigenvectors of $\hat{\mathcal{H}}$ is obtained by $\mathbf{e}_i = V\tilde{\mathbf{e}}_i$, where $\tilde{\mathbf{e}}_i$ are the eigenvectors of T_n . From V , we can obtain the eigenvectors of $\hat{\mathcal{H}}$ by performing the Lanczos method. However, in the actual calculations, it is difficult to keep V because its dimension is large [dimension of $V = (\text{dimension of the total Hilbert space}) \times (\# \text{ of Lanczos iterations})$]. Thus, to obtain the eigenvectors, we again perform the same Lanczos calculations after we obtain the eigenvalues from the Lanczos methods. In the first Lanczos calculation, we keep $\tilde{\mathbf{e}}_i$ because its dimension is small ^{*2}. From this procedure, we obtain the eigenvectors from V .

In the Lanczos method, within a few hundred or thousand Lanczos iterations, we obtain the accurate eigenvalues near the maximum and minimum values of eigenvalues. The necessary number of iterations is small enough compared to the dimensions of the total Hilbert space. We note that it is shown that the errors of the maximum and minimum eigenvalues becomes exponentially small as a function of Lanczos iteration (for details, see Ref. [8]).

5.1.2 Inverse iteration method

From the approximate value of the eigenvalues (E_n), by successively operating $(\hat{\mathcal{H}} - E_n)^{-1}$ to the initial vector \mathbf{y}_0 , we can obtain the accurate eigenvector for E_n .

From $(\hat{\mathcal{H}} - E_n)^{-1}\mathbf{y}_0$, we obtain the linear simultaneous equations such as

$$\mathbf{y}_k = (\hat{\mathcal{H}} - E_n)\mathbf{y}_{k+1}. \quad (5.8)$$

By solving this equation by using the conjugate gradient method (CG method), we obtain the eigenvector. From the obtained eigenvector, we can calculate the eigenvalues and correlation functions. We note that additional four vectors are necessary to perform the CG method. For large system size, it may be impossible to allocate memory to the additional vectors.

^{*2}upper bound of the dimensions of $\tilde{\mathbf{e}}_i$ is $\#$ of Lanczos iterations.

5.1.3 Details of implementation

In $\mathcal{H}\Phi$, we use `dsyev` (routine of lapack) for diagonalization of T_n . We use the energy of the first excited state of T_n as a criteria of convergence. In the standard setting, after five Lanczos step, we diagonalize T_n every two Lanczos step. If the energy of the first excited states coincides with the previous energy within the specified accuracy, the Lanczos iteration finishes. The accuracy of the convergence can be specified by `CDataFileHead` (ModPara file in the expert mode).

After obtaining the eigenvalues, we again perform the Lanczos iteration to obtain the eigenvector. From the eigenvectors $|n\rangle$, we calculate energy $E_n = \langle n|\hat{\mathcal{H}}|n\rangle$ and variance $\Delta = \langle n|\hat{\mathcal{H}}^2|n\rangle - (\langle n|\hat{\mathcal{H}}|n\rangle)^2$. If E_n coincides with the eigenvalues obtained by the Lanczos iteration and Δ is smaller than the specified value, we finish diagonalization.

If the accuracy of Lanczos method is not enough, we perform the CG method to obtain the eigenvector. As an initial vector of the CG method, we use the eigenvectors obtained by the Lanczos method in the standard setting. This often accelerates the convergence.

5.2 Full Diagonalization method

5.2.1 Over view

We generate matrix of \hat{H} by using the real space configuration $|\psi_j\rangle$ ($j = 1 \cdots d_H$, d_H is dimension of the Hilbert space): $H_{ij} = \langle \psi_i|\hat{H}|\psi_j\rangle$. By diagonalizing this matrix, we can obtain all the eigenvalues E_i and eigenvectors $|\Phi_i\rangle$ ($i = 1 \cdots d_H$). In the diagonalization, we use lapack routine such as `dsyev` or `zheev`. We also calculate and out put the expectation values $\langle A_i \rangle \equiv \langle \Phi_i|\hat{A}|\Phi_i\rangle$. These values are used for the finite-temperature calculations.

5.2.2 Finite-temperature calculations

From $\langle A_i \rangle \equiv \langle \Phi_i|\hat{A}|\Phi_i\rangle$, we calculate finite-temperature properties by using the relation

$$\langle \hat{A} \rangle = \frac{\sum_{i=1}^N \langle A_i \rangle e^{-\beta E_i}}{\sum_{i=1}^N e^{-\beta E_i}}. \quad (5.9)$$

In the actual calculation are performed as the post scripts.

5.3 Finite-temperature calculations by TPQ method

Sugiura and Shimizu show that it is possible to calculate the finite-temperature properties from a few wavefunctions (in the thermodynamic limit, only one wave function is necessary) [5]. The wavefunction is called thermal pure quantum (TPQ) state. Because TPQ state can be generated by operating the Hamiltonian to the random initial wavefunction, we directly use the routine Lanczos method to the TPQ

calculations. Here, we explain how to construct micro canonical TPQ (mTPQ) state, which offers the simplest way for finite-temperature calculations.

Let $|\psi_0\rangle$ a random initial vector. By operating $(l - \hat{H}/N_s)^k$ (l is constant, N_s represents number of sites) to $|\psi_0\rangle$, we obtain the k th TPQ states as

$$|\psi_k\rangle \equiv \frac{(l - \hat{H}/N_s)|\psi_{k-1}\rangle}{|(l - \hat{H}/N_s)|\psi_{k-1}\rangle|}. \quad (5.10)$$

From $|\psi_k\rangle$, we estimate corresponding inverse temperature β_k as

$$\beta_k \sim \frac{2k/N_s}{l - u_k}, \quad u_k = \langle \psi_k | \hat{H} | \psi_k \rangle / N_s, \quad (5.11)$$

where u_k is the internal energy. Arbitrary local physical properties at β_k is also estimated as

$$\langle \hat{A} \rangle_{\beta_k} = \langle \psi_k | \hat{A} | \psi_k \rangle / N_s. \quad (5.12)$$

In finite-size system, error is caused by the choice of the initial random vector. To estimate the average value and error of the physical properties, we perform some independent calculations by changing $|\psi_0\rangle$.

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