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INTRODUCTION TO MCTDH

LECTURE NOTES

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Abbreviations

CAP	Complex Absorbing Potential
CDVR	Correlation Discrete Variable Representation
CI	Configuration Interaction
CMF	Constant Mean Field
CPU	Central Process Unit
D	Dimension
DF	Dirac-Frenkel
DOF	Degree Of Freedom
DVR	Discrete Variable Representation
EOM	Equation Of Motion
FBR	Finite Basis Representation
FD	Filter Diagonalization
GB	Gigabyte
GS	Ground State
IR	Infrared
KB	Kilobyte
MB	Megabyte
MCTDH	Multiconfiguration Time-Dependent Hartree
PB	Petabyte
PDE	Partial Differential Equation
PES	Potential Energy Surface
RPA	Ramdon-Phase Approximation
SE	Schrödinger Equation
SIL	Short Iterative Lanczos

SPF Single Particle Function
SPP Single Particle Potential
TB Terabyte
TD Time Dependent
TD-DVR Time-Dependent Discrete Variable Representation
TDH Time-Dependent Hartree
TDHF Time-Dependent Hartree-Fock
TDSE Time Dependent Schrödinger Equation
TIH Time-Independent Hartree
TISE Time Independent Schrödinger Equation
VP Variational Principle
WF Wave Function
WP Wave Packet

Chapter 1

Introduction to Quantum Dynamics

1.1 Time-dependent versus time-independent methods

If the Hamiltonian is time-dependent, *e.g.* because there is a coupling to an external electromagnetic field, the time-dependent (TD) version of the Schrödinger equation (TDSE) obviously must be used^{1,2}

$$i\dot{\Psi}(\mathbf{q}, t) = \hat{H}(t)\Psi(\mathbf{q}, t) \quad (1.1)$$

However, one often deals with systems where the Hamiltonian is time-independent. When solving those problems, why engage the seemingly complicated TD version of the Schrödinger equation, why not turn to the time-independent (TI) one?

$$\hat{H}\Psi_n(\mathbf{q}) = E_n\Psi_n(\mathbf{q}) \quad (1.2)$$

In the time-dependent Schrödinger equation there appears one more variable, the time. But mathematically the TDSE is a simpler equation than the time-independent one. The TDSE is an initial value problem of a first order differential equation, a very simple mathematical problem except that it is of very high, in fact infinite, dimensionality. The TISE poses an eigenvalue problem which is more complicated. The dimensionality of both problems is the same, provided one uses identical discretization schemes (basis sets, grids, etc.). Which method, TD or TI, is more appropriate, depends on the problem to be solved. The TDSE may need to be solved over a long time interval and the TISE may have to provide many eigenstates. If only the ground-state (GS) is desired (this is not a dynamical problem, though) then the TISE is the obvious method of choice. However, even for obtaining a ground state wavefunction the TD method is quite often used, although with a slight modification: propagation in imaginary time, the so called relaxation method. We will discuss this later.

¹Except for purely periodic interactions when one may use the Floquet-Theorem to transform the problem to a time-independent one.

²We use a unit system with $\hbar = 1$ throughout.

The TD method is of advantage if the propagation time needed is rather short. Obviously, the numerical effort increases, at least linearly, with propagation time. Hence, scattering and half-scattering processes are particularly well suited for being treated within the TD picture. Firstly, because the interaction time is finite and often rather short. And secondly, because one has to deal with continua. The inclusion of continua makes the solution of the TISE much harder. The SE has to be solved with respect to complicated boundary conditions. The eigenvalue equation

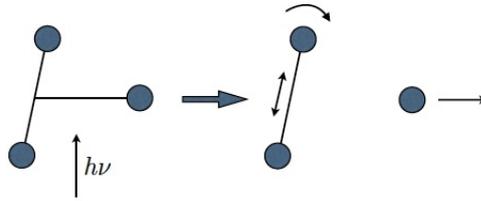
$$H\Psi_E = E\Psi_E \quad (1.3)$$

is then solved for a set of fixed energies (every energy is an eigenvalue, we are in a continuum), usually by solving spatial differential equations on a grid.

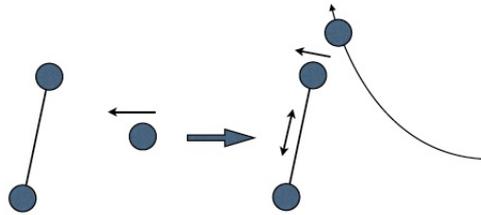
In the TD world, however, one propagates a wavepacket (WP), and there is no difference in propagating a wavepacket which is a superposition of bound-states to a superposition of continuum states. It is the same propagation algorithm but possibly on longer grids.

Let us draw some pictures of scattering or half-scattering problems.:

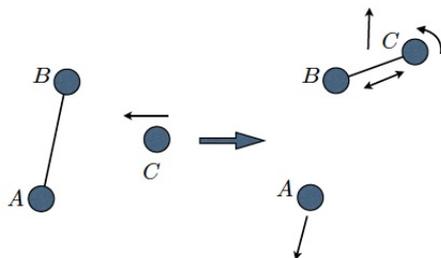
- Photodissociation:



- Inelastic scattering:



- Reactive scattering:



It can be easily seen that the TD method requires three steps:

- (1) Preparation of the initial state $\Psi(0)$.
- (2) Propagation: $\Psi(0) \rightarrow \Psi(t)$.
- (3) Analysis: $\Psi(t) \rightarrow$ observables (cross-sections, spectra, etc.).

1.2 Initial state

We discuss by two typical examples how to choose an initial state.

1.2.1 Photodissociation

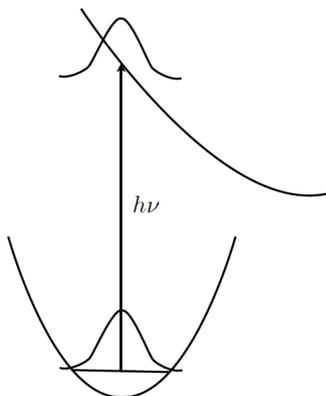


Figure 1.1: Photodissociation initial step.

When studying photodissociation, the initial state is the vibrational ground state (GS) of the electronic ground state potential energy surface (PES) placed on an excited state PES (Condon approximation, see Fig.1.1). In a more general case, the initial state is the GS multiplied with a dipole operator surface.

1.2.2 Inelastic scattering, reactive scattering

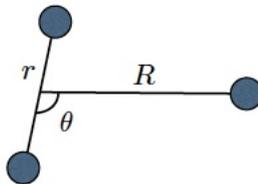


Figure 1.2: Definition of Jacobi coordinates for a triatomic molecule.

For inelastic or reactive scattering, one may take a Hartree product as initial state

$$\Psi(t=0; \theta, r, R) = \Psi_1(\theta) \Psi_2(r) \Psi_3(R) \quad (1.4)$$

$$\Psi_1(\theta) = \text{const.} \times P_j(\cos\theta)$$

$$\Psi_2(r) = \text{eigenfunction of vibrational Hamiltonian}$$

$$\Psi_3(R) = \text{many choices possible, usually gaussian times plane wave}$$

This makes it clear that we obtain only information with respect to the initial state. *E.g.* if in the inelastic scattering problem the initial state is chosen such, that the diatom is in its ($j=0, v=0$) quantum state, then we can obtain only the cross sections

$$\sigma(E, (0,0) \rightarrow (j'', v'')) \quad (1.5)$$

To obtain the cross sections

$$\sigma(E, (j', v') \rightarrow (j'', v'')) \quad (1.6)$$

one has to run a propagation with a wavepacket initially in (j', v') . Furthermore, the initial state of relative motion, $\Psi_3(R)$, its velocity distribution, determines the energy range investigated.

To discuss this more formally, we inspect the S-matrix. With a TI method one always computes the full S-matrix for one energy

$$S(E) = \begin{pmatrix} \vdots & & \dots \\ & \ddots & \vdots \\ \vdots & \ddots & \\ & & \dots \end{pmatrix} \quad (1.7)$$

whereas a TD method generates one column of the S-matrix for a range of energies.

$$S(E) = \begin{pmatrix} \Psi(0) \\ | \\ | \\ | \end{pmatrix} \quad (1.8)$$

That only one column is generated is not a disadvantage, it is in fact an advantage! For large systems one does not want to know all state-to-state cross sections or, more generally, all quantum information. Only a selected set of information is wanted. Using the TD picture it is much easier to concentrate on the desired observables as compared to the TI picture.

Turning to the numerical representation of a WP we note another advantage of the TD picture and this one is probably the most important one for approximate methods. The TD WP (at each instant of time), is less structured and hence easier to represent compared to eigenstates (except for the GS). Time Dependent Hartree (TDH) is known to yield better eigenenergies than TIH. In electronic structure theory TDHF is known to be equivalent to the Random-Phase Approximation (RPA) which contains some correlation.

To give another example. In the the 70s, Heller introduced Gaussian WP propagation. He wrote the WP as

$$\Psi(x, t) = \exp[-\alpha(t) \cdot (x - x_0(t))^2 - ip_0(t) \cdot x + \gamma(t)] \quad (1.9)$$

and derived EOM for the parameters α , x_0 , p_0 , and γ .

This is a simple, crude method, but for several systems it provides useful information; spectra, etc. While approximating a time-dependent WP by a Gaussian may work reasonably well, approximating eigenstates by Gaussians is useless. Only the GS can be approximated by a single Gaussian.

1.3 Analysis

We want to give some examples for the analysis step

$$\Psi(t) \rightarrow \text{observables}$$

1.3.1 Power spectrum

$$\sigma(E) = \langle \Psi | \delta(E - H) | \Psi \rangle \quad (1.10)$$

If the spectrum is discrete, we can insert the completeness relation

$$\mathbf{1} = \sum_n |\Psi_n\rangle \langle \Psi_n|$$

where

$$H\Psi_n = E\Psi_n$$

then

$$\begin{aligned} \sigma(E) &= \sum_{n,m} \langle \Psi | \Psi_n \rangle \langle \Psi_n | \delta(E - H) | \Psi_m \rangle \langle \Psi_m | \Psi \rangle \\ &= \sum_{n,m} \langle \Psi | \Psi_n \rangle \delta(E - E_n) \delta_{n,m} \langle \Psi_m | \Psi \rangle \\ &= \sum_n |C_n|^2 \delta(E - E_n) \end{aligned} \quad (1.11)$$

with

$$C_n = \langle \Psi_n | \Psi \rangle \quad (1.12)$$

and hence

$$\Psi = \sum_n C_n \Psi_n \quad (1.13)$$

Turning to the time-dependent picture, we use the Fourier representation of the δ -function

$$\delta(E) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{iEt} dt \quad (1.14)$$

$$\begin{aligned} \sigma(E) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \langle \Psi | e^{i(E-H)t} | \Psi \rangle dt \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{iEt} \langle \Psi | \Psi(t) \rangle dt \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{iEt} a(t) dt \end{aligned} \quad (1.15)$$

with the autocorrelation function

$$a(t) = \langle \Psi | e^{-iHt} | \Psi \rangle = \langle \Psi | \Psi(t) \rangle \quad (1.16)$$

The integration over negative time is cumbersome, but can easily be avoided. If the Hamiltonian is hermitian, one finds

$$a(-t) = \langle \Psi | e^{iHt} | \Psi \rangle = \langle e^{-iHt} \Psi | \Psi \rangle = \langle \Psi | e^{-iHt} | \Psi \rangle^* = [a(t)]^* \quad (1.17)$$

Thus

$$\int_{-\infty}^0 e^{iEt} a(t) dt = \int_0^{\infty} e^{-iEt} a(-t) dt = \int_0^{\infty} [e^{iEt} a(t)]^* dt \quad (1.18)$$

$$\sigma(E) = \frac{1}{2\pi} \int_0^{\infty} ([e^{iEt} a(t)]^* + e^{iEt} a(t)) dt = \frac{1}{\pi} \text{Re} \int_0^{\infty} e^{iEt} a(t) dt \quad (1.19)$$

More tricks are possible

$$\begin{aligned} a(t) &= \langle \Psi | e^{-iHt} | \Psi \rangle \\ &= \langle e^{iH^\dagger t/2} \Psi | e^{-iHt/2} \Psi \rangle \\ &= \langle (e^{-iH^\dagger t/2} \Psi^*)^* | e^{-iHt/2} \Psi \rangle \\ &= \langle \Psi(t/2)^* | \Psi(t/2) \rangle \end{aligned} \quad (1.20)$$

where the last step requires a real initial state ($\Psi^* = \Psi$) and a symmetric Hamiltonian

$$H = H^T = H^{\dagger*} \quad (1.21)$$

This so-called $t/2$ -trick is very useful because it provides an autocorrelation function which is twice as long as the propagation. In general, one wants to use both, Eq. (1.19) and Eq. (1.20). This requires a real-symmetric Hamiltonian. Fortunately, real-symmetric Hamiltonians augmented with a complex absorbing potential (CAP) are not excluded. A closer analysis shows that the sign of a

CAP has to be inverted when propagating in negative time. This keeps Eq. (1.17-1.19) valid even for CAP augmented real-symmetric Hamiltonians.

One will never be able to perform the propagation up to $t = \infty$ but will stop at some finite time T . Rather than replacing the upper integral limit by T , we introduce a window function $g(t)$

$$\sigma_g(E) = \frac{Re}{\pi} \int_0^\infty e^{iEt} g(t) a(t) dt = \frac{1}{2\pi} \int_{-\infty}^\infty e^{iEt} g(t) a(t) dt \quad (1.22)$$

and require

$$0 \leq g(t) \leq 1, \quad g(0) = 1, \quad g(t) = 0 \text{ for } |t| > T, \quad g(t) = g(-t) \quad (1.23)$$

As well known, the Fourier transform of a product of two functions is equal to the convolution of the Fourier transforms of the two functions. *I.e.*

$$\begin{aligned} \sigma_g(E) &= (\sigma * \tilde{g})(E) \\ &= \int \sigma(\epsilon) \tilde{g}(E - \epsilon) d\epsilon \\ &= \int \sigma(E - \epsilon) \tilde{g}(\epsilon) d\epsilon \end{aligned}$$

where

$$\tilde{g}(\epsilon) = \frac{1}{2\pi} \int_{-\infty}^\infty e^{i\epsilon t} g(t) dt$$

The proof is simple, we use

$$\delta(\tau - t) = \frac{1}{2\pi} \int e^{i(\tau-t)\epsilon} d\epsilon \quad (1.24)$$

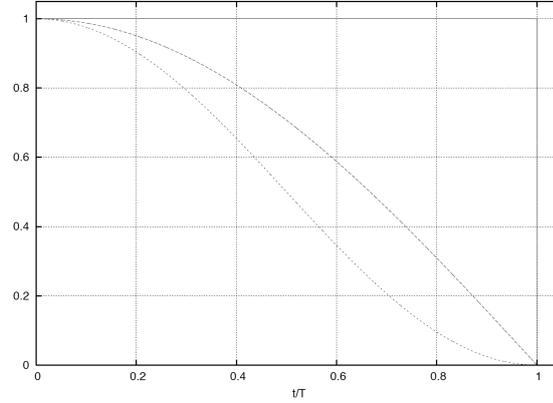
$$\begin{aligned} \sigma_g(E) &= \frac{1}{2\pi} \int_{-\infty}^\infty e^{iEt} g(t) a(t) dt \\ &= \frac{1}{2\pi} \int \int e^{iEt} g(\tau) a(t) \delta(\tau - t) dt d\tau \\ &= \frac{1}{(2\pi)^2} \int \int \int e^{iEt} a(t) e^{-i\epsilon t} e^{i\epsilon\tau} g(\tau) d\tau dt d\epsilon \\ &= \frac{1}{2\pi} \int \int e^{i(E-\epsilon)t} a(t) \tilde{g}(\epsilon) dt d\epsilon \\ &= \int \sigma(E - \epsilon) \tilde{g}(\epsilon) d\epsilon \end{aligned} \quad (1.25)$$

We now can choose g to have compact support, *i.e.*

$$g(t) = 0 \quad \text{if } |t| > T \quad (1.26)$$

In particular, we inspect the three window functions

$$g_k(t) = \cos^k \left(\frac{\pi t}{2T} \right) \theta \left(1 - \frac{|t|}{T} \right) \quad (1.27)$$

Figure 1.3: Window functions g_0 , g_1 , and g_2 .

for $k = 0, 1, 2$.

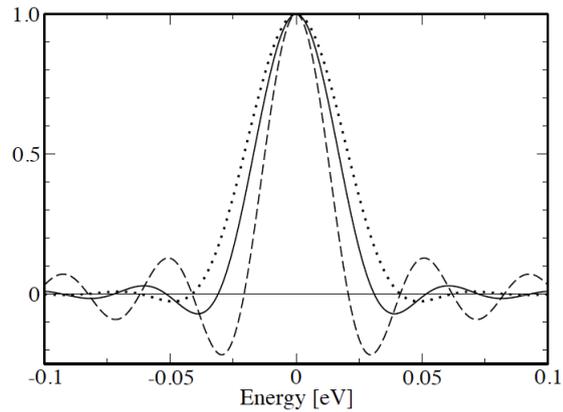
The Fourier-transforms read

$$\tilde{g}_0(\omega) = \frac{\sin(\omega T)}{\pi \omega} \quad (1.28)$$

$$\tilde{g}_1(\omega) = \frac{2T \cos(\omega T)}{(\pi - 2\omega T)(\pi + 2\omega T)} \quad (1.29)$$

$$\tilde{g}_2(\omega) = \frac{\pi \sin(\omega T)}{2\omega (\pi - \omega T)(\pi + \omega T)} \quad (1.30)$$

The oscillations caused by the box-filter ($k = 0$) are known as Gibbs phenomena. To avoid or at least lessen those we use in general g_1 or g_2 . Note that the better filter leads to broader lines.

Figure 1.4: Reduction of the Gibbs phenomenon by application of window functions: (i) g_0 , dashed line; (ii) g_1 , solid line; (iii) g_2 , dotted line.

The power spectrum, although very useful, is an academic quantity. Let us turn to real spectra, *e.g.* absorption spectra.³

$$I(\omega) = \frac{\pi\omega}{3c\epsilon_0\hbar^2} \sum_n |\langle \Psi_n^{(f)} | \mu | \Psi_0^{(i)} \rangle|^2 \delta(\hbar\omega + E_0^{(i)} - E_n^{(f)}) \quad (1.31)$$

μ is the transition operator, usually the dipole operator (μ has three components. As the molecule freely rotates one averages over the three intensities). For electronic spectra one often adopts the Condon approximation and sets $\mu = 1$. $\Psi_n^{(f)}$ and $E_n^{(f)}$ are the exact eigenstates and energies of the final PES and similar for the superscript (i), which refers to the initial electronic state.

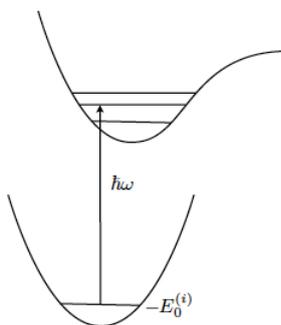


Figure 1.5: Electronic transition.

On the other hand, infrared spectroscopy is characterized by the initial and final electronic states been identical, $i = f$.

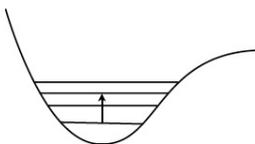


Figure 1.6: Infrared absorption.

We now rearrange the sum

$$\begin{aligned} & \sum_n \langle \Psi_0^{(i)} | \mu^\dagger | \Psi_n^{(f)} \rangle \delta(\hbar\omega + E_0^{(i)} - E_n^{(f)}) \langle \Psi_n^{(f)} | \mu | \Psi_0^{(i)} \rangle \\ &= \langle \Psi_0^{(i)} | \mu^\dagger \delta(\hbar\omega + E_0^{(i)} - H) \mu | \Psi_0^{(i)} \rangle \\ &= \langle \Psi_\mu | \delta(\hbar\omega + E_0^{(i)} - H) | \Psi_\mu \rangle \end{aligned} \quad (1.32)$$

with $\Psi_\mu = \mu | \Psi_0^{(i)} \rangle$.

³Usually $\hbar = 1$, but here we reintroduce \hbar .

Hence

$$I(\omega) = \frac{\pi\omega}{3c\epsilon_0\hbar^2} \sigma_{\text{Power}, \Psi_\mu}(\hbar\omega + E_0^{(i)}) \quad (1.33)$$

Most of the observables one wants to compute are determined by a Fourier transform of some correlation function.

1.4 Autocorrelation functions

The wave function may consist of a discrete and a continuous part:

$$\Psi = \sum_n C_n \varphi_n + \int_{E_c}^{\infty} C(E) \varphi_E dE \quad (1.34)$$

with

$$\begin{aligned} H\varphi_n &= E_n\varphi_n & (E_n \leq E_c, E_c \text{ is the threshold for continuum}) \\ H\varphi_E &= E\varphi_E & (E > E_c) \end{aligned}$$

and

$$\langle \varphi_n | \varphi_m \rangle = \delta_{n,m} \quad \langle \varphi_n | \varphi_E \rangle = 0 \quad \langle \varphi_E | \varphi_{E'} \rangle = \delta(E - E') \quad (1.35)$$

$$C_n = \langle \varphi_n | \Psi \rangle, \quad C(E) = \langle \varphi_E | \Psi \rangle \quad (C(E) = 0 \text{ for } E \leq E_c) \quad (1.36)$$

The power spectrum

$$\sigma(E) = \langle \Psi | \delta(E - H) | \Psi \rangle \quad (1.37)$$

is then given by

$$\sigma(E) = \sum_n |C_n|^2 \delta(E - E_n) + |C(E)|^2 \quad (1.38)$$

Switching to the time-dependent picture, we write the wave function as

$$\Psi(t) = \sum_n C_n \varphi_n e^{-iE_n t} + \int_{E_c}^{\infty} C(\epsilon) \varphi_\epsilon e^{-i\epsilon t} d\epsilon \quad (1.39)$$

The autocorrelation function then becomes

$$a(t) = \langle \Psi(0) | \Psi(t) \rangle = \sum_n |C_n|^2 e^{-iE_n t} + \int_{E_c}^{\infty} |C(\epsilon)|^2 e^{-i\epsilon t} d\epsilon \quad (1.40)$$

and the power spectrum in terms of the autocorrelation function is given by Eq. (1.19) or, when using a window function, by Eq. (1.22). It is illustrative to show some autocorrelation functions and the spectra generated from them.

The autocorrelation function of the photodissociation of NOCl vanishes quickly (Fig.1.7). Figure 1.8 shows two spectra generated from this autocorrelation function, one using the window g_0 and the other using g_2 . (The spectrum generated with window g_1 lies in between). As the autocorrelation goes to zero, there are no artifacts caused by the Gibbs phenomenon and the window g_0 performs well. The filters g_1 and g_2 wash out the structure of the spectrum and hence should not be used in the present case.

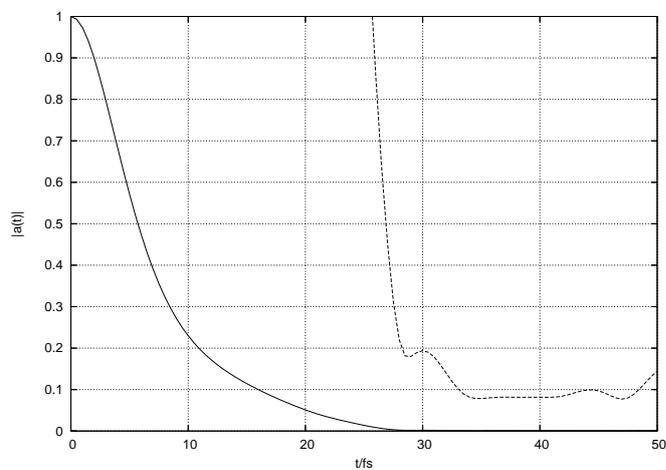


Figure 1.7: Absolute value of the autocorrelation function of the photodissociation process $NOCl \rightarrow NO + Cl$. The dashed line displays $100 \cdot |a(t)|$.

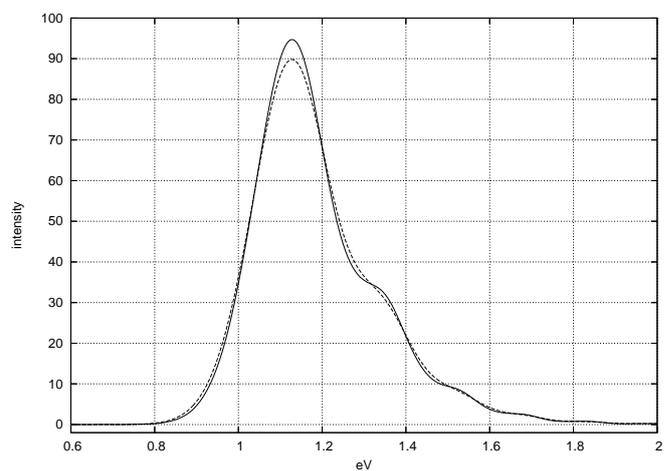


Figure 1.8: Power spectrum generated from the autocorrelation function Fig. 1.7. The full and dashed line spectra were generated with the window g_0 and g_2 respectively.

As a next example, we discuss the autocorrelation and spectrum of photoexcited pyrazine. This is a molecule with 24 degrees of freedom and very complicated dynamics as a conical intersection couples the S_1 and S_2 electronic states. Due to this, an enormous large number of vibrational (or more precisely vibronic) states contribute to the sum in Eq. (1.40).

Although this is a bounded system with no contribution from a continuum, the autocorrelation drops quickly, due to destructive interference in the sum in Eq. (1.40). After 50 fs the autocorrelation oscillates around ~ 0.015 but does not decrease further. This is shown in Fig. 1.9.

The spectra generated from this autocorrelation using different window functions are shown in Fig. 1.10. Using the g_0 window the spectrum shows strong negative parts caused by the Gibbs phenomenon. The spectrum in the middle, which is generated with the g_1 window is much clearer, and the g_2 generated spectrum is even smoother. However, it almost washes out some small oscillations, *e.g.* between 2.3 and 2.4 eV. Hence, the g_1 window seems to be the best choice in this case.

The unphysical negative parts of a spectrum originate from two causes. The first cause is the Gibbs phenomenon, *i.e.* the chopping of the autocorrelation function at $t = T$. For this the window functions were introduced and going from g_0 to g_1 and g_2 will substantially reduce this artifact (see Fig. 1.4). The other cause is an inaccurate autocorrelation function. Small errors in the autocorrelation may lead to small negative parts in the spectrum. These errors are only weakly modified by the window function. In such a case, a more accurate propagation helps.

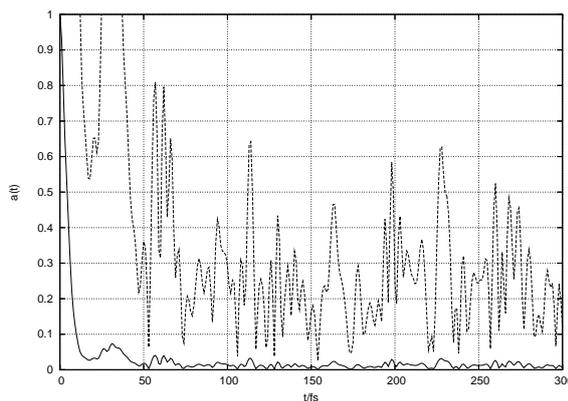


Figure 1.9: Absolute value of the autocorrelation function of the photoexcited pyrazine. The dashed line shows the autocorrelation enlarged by a factor of 20.

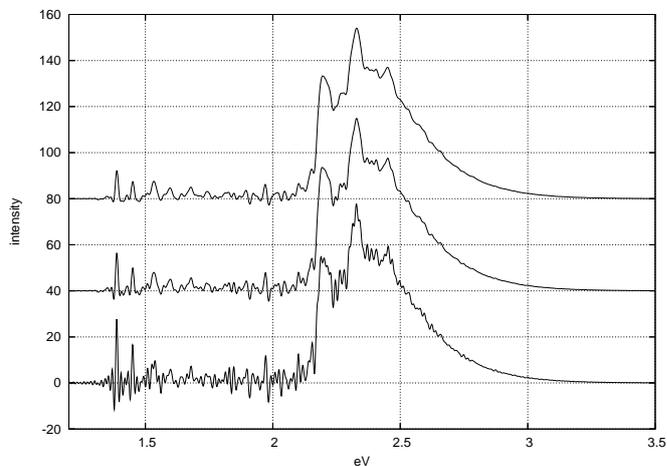


Figure 1.10: Pyrazine spectra generated from the autocorrelation function (Fig.1.9) using different window functions.

As third example, we discuss the (bending) excitation of water (Figs.1.11 and 1.12) show the autocorrelation function and spectrum for this model. This is a bound state problem where only a few eigenstates contribute. The autocorrelation function is oscillatory but does not decay. Generating the spectrum with the g_0 window leads to strong artificial oscillations, a beautiful demonstration of the Gibbs phenomenon. The g_1 spectrum (middle) is much improved but in this case the g_2 spectrum (top) is clearly the best.

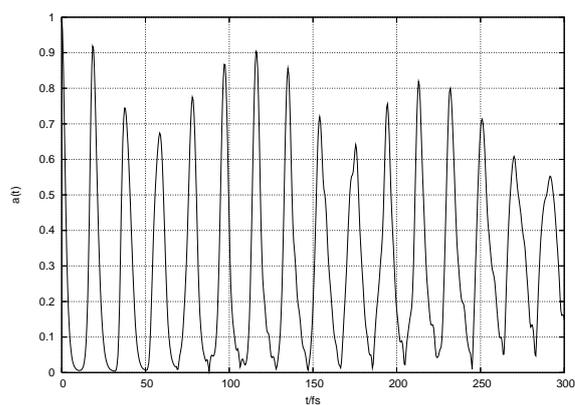


Figure 1.11: Oscillatory autocorrelation function for H_2O .

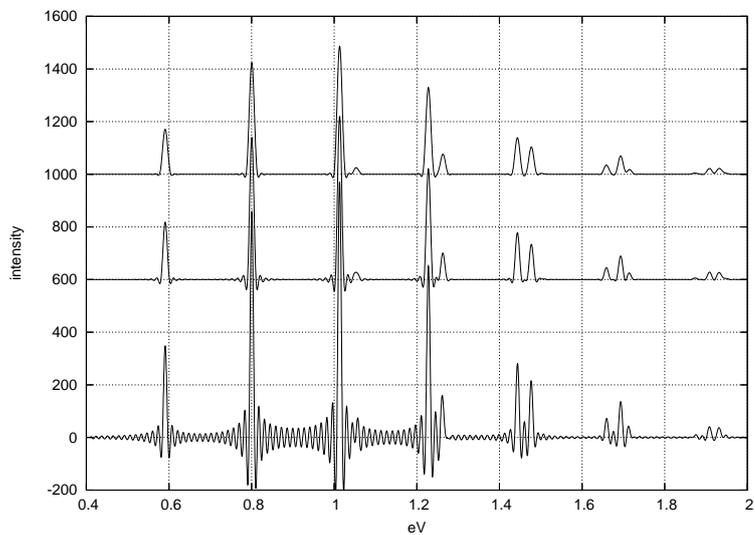


Figure 1.12: Spectrum of H_2O for different window functions. The spectrum is generated from the autocorrelation function displayed in Fig. 1.11. The spectrum obtained with the window functions g_1 and g_2 are shifted upwards by 600 and 1000 units, respectively.

Chapter 2

Standard method and TDH

2.1 Variational Principles

There are three well-known time-dependent variational principles

- Dirac-Frenkel:

$$\langle \delta\Psi | H - i\frac{\partial}{\partial t} | \Psi \rangle = 0 \quad (2.1)$$

- McLachlan:

$$\delta\|\theta - H\Psi\|^2 = 0 \quad (\|\theta - H\Psi\|^2 = \min) \quad (2.2)$$

where θ is varied and $i\dot{\Psi} = \theta$

- Lagrange:

$$\delta \int_{t_1}^{t_2} \langle \Psi | H - i\frac{\partial}{\partial t} | \Psi \rangle dt = 0 \quad (2.3)$$

with the condition that the variation of the integrand vanishes for $t = t_1$ and $t = t_2$.

McLachlan's principle is equivalent to

$$\text{Im} \langle \delta\Psi | H - i\frac{\partial}{\partial t} | \Psi \rangle = 0 \quad (2.4)$$

if the variational spaces of Ψ and $\dot{\Psi}$ are identical, *i.e.*

$$\{\delta\dot{\Psi}\} = \{\delta\Psi\} \quad (2.5)$$

Analogously, Lagrange's principle implies

$$\text{Re} \langle \delta\Psi | H - i\frac{\partial}{\partial t} | \Psi \rangle = 0 \quad (2.6)$$

If all parameters are complex analytic then $i\delta\Psi$ is an allowed variation when $\delta\Psi$ is an allowed variation and all the variational principles discussed are identical! Hence we use Dirac-Frenkel, which is the simplest.

2.2 The standard method

The most direct way to solve the TDSE is to expand the WF into a product of TI basis set.

$$\Psi(q_1, q_2, \dots, q_f, t) = \sum_{j_1 \dots j_f} C_{j_1 \dots j_f}(t) \chi_{j_1}^{(1)}(q_1) \dots \chi_{j_f}^{(f)}(q_f) \quad (2.7)$$

where the χ_j are orthonormal basis functions, *e.g.* harmonic oscillator (HO) functions, Legendre functions, plane waves, etc. In electronic structure theory this would be called a full-CI approach.

The goal is now to derive equations of motion for the coefficients C . For this, we employ the Dirac-Frenkel variational principle (VP), Eq. (2.1). Since the objects to be varied here are just numbers, the variation is a partial differentiation:

$$\delta\Psi = \sum_{l_1 \dots l_f} \frac{\partial\Psi}{\partial C_{l_1 \dots l_f}} \delta C_{l_1 \dots l_f} = \sum_{l_1 \dots l_f} \chi_{l_1}^{(1)}(q_1) \dots \chi_{l_f}^{(f)}(q_f) \delta C_{l_1 \dots l_f} \quad (2.8)$$

and

$$\dot{\Psi} = \sum_{j_1 \dots j_f} \dot{C}_{j_1 \dots j_f} \chi_{j_1}^{(1)} \dots \chi_{j_f}^{(f)} \quad (2.9)$$

Because the variations are independent one may set

$$\delta C_{l_1 \dots l_f} = \begin{cases} 1 & \text{for } l_1 \dots l_f = l_1^{(0)} \dots l_f^{(0)} \\ 0 & \text{else} \end{cases}$$

From $\langle \delta\Psi | H - i \frac{\partial}{\partial t} | \Psi \rangle = 0$, and replacing $l_\kappa^{(0)}$ by l_κ , we obtain

$$\begin{aligned} \langle \chi_{l_1} \dots \chi_{l_f} | \sum_{j_1 \dots j_f} C_{j_1 \dots j_f} H \chi_{j_1} \dots \chi_{j_f} \rangle = \\ i \langle \chi_{l_1} \dots \chi_{l_f} | \sum_{j_1 \dots j_f} \dot{C}_{j_1 \dots j_f} \chi_{j_1} \dots \chi_{j_f} \rangle \end{aligned} \quad (2.10)$$

or

$$\sum_{j_1 \dots j_f} \langle \chi_{l_1} \dots \chi_{l_f} | H | \chi_{j_1} \dots \chi_{j_f} \rangle C_{j_1 \dots j_f} = i \dot{C}_{l_1 \dots l_f} \quad (2.11)$$

and defining composite indices $J = (j_1, \dots, j_f)$ and configurations $\chi_J = \prod_{\kappa=1}^f \chi_{j_\kappa}$

$$\boxed{i \dot{C}_L = \sum_J \langle \chi_L | H | \chi_J \rangle C_J} \quad (2.12)$$

This is a very simple first order differential equation with constant coefficients. It has the formal solution (for time-independent Hamiltonians)

$$\mathbf{C}(t) = e^{-i\mathbf{H}t} \mathbf{C}(0) \quad (2.13)$$

where the bold faces shall indicate the vector and matrix form of coefficients and Hamiltonian, respectively. This differential equation is difficult to solve,

because the number of coupled equations, its dimension, is large.

In general one needs at least 10 basis functions per degree of freedom. Hence, there are about 10^f coupled equations to be solved. Consider a molecule with 6 atoms, then there are $f = 3N - 6 = 12$ degrees of freedom, and 10^{12} coupled equations. This is not doable. In general only up to 4 atom systems ($6D$) may be treated by the standard method with today's computers. One hence has to resort to cleverer, but also more approximate methods.

2.3 The Time-dependent Hartree approach (TDH)

One of the simplest propagation methods is the TDH approach.

$$\Psi(q_1, q_2, \dots, q_f, t) = a(t) \varphi_1(q_1, t) \cdots \varphi_f(q_f, t) \quad (2.14)$$

The representation is not unique because

$$\varphi_1 \cdot \varphi_2 = \left(\frac{\varphi_1}{b}\right) \cdot (\varphi_2 \cdot b) \quad (2.15)$$

holds for any complex constant $b \neq 0$.

The additional factor $a(t)$ increases the redundancy, but because of this coefficient there is now a free factor for each function φ_κ , called *single particle function* (SPF). All SPFs are now treated on the same footing. To arrive at unique equations of motion one has to introduce constraints, which remove the non-uniqueness but do not narrow the variational space.¹

If a function changes in time by a complex factor only, then this is equivalent to a time derivative which is always in the direction of the function itself

$$\dot{\varphi} \propto \varphi$$

To see this more explicitly, write

$$\varphi = \alpha \cdot \tilde{\varphi} \quad \text{with } \|\tilde{\varphi}\| = 1 \quad (2.16)$$

$$\dot{\varphi} = \dot{\alpha} \tilde{\varphi} + \alpha \dot{\tilde{\varphi}} \quad (2.17)$$

$$\langle \varphi | \dot{\varphi} \rangle = \alpha^* \dot{\alpha} + |\alpha|^2 \langle \tilde{\varphi} | \dot{\tilde{\varphi}} \rangle \quad (2.18)$$

This shows that we can prescribe $\langle \varphi | \dot{\varphi} \rangle$ any value, such a prescription will merely determine $\dot{\alpha}$.

Hence, we propose the constraints

$$i \langle \varphi_\kappa(t) | \dot{\varphi}_\kappa(t) \rangle = g_\kappa(t) \quad (2.19)$$

We would like to conserve the norm of the SPFs

$$\frac{d}{dt} \|\varphi_\kappa\|^2 = \frac{d}{dt} \langle \varphi_\kappa | \varphi_\kappa \rangle \quad (2.20)$$

$$= \langle \dot{\varphi}_\kappa | \varphi_\kappa \rangle + \langle \varphi_\kappa | \dot{\varphi}_\kappa \rangle \quad (2.21)$$

$$= 2 \operatorname{Re} \langle \varphi_\kappa | \dot{\varphi}_\kappa \rangle = 2 \operatorname{Im} g_\kappa \quad (2.22)$$

which implies that the norm is conserved if the constraints g_κ are real.

¹*E.g.* the constraint $\dot{\varphi} = 0$ would dramatically narrow the variational space.

2.3.1 TDH equations

In the TDH approach, the WF is expressed as

$$\Psi(q_1, q_2, \dots, q_f, t) = a(t) \prod_{\kappa=1}^f \varphi_{\kappa}(q_{\kappa}, t) = a(t) \cdot \Phi(t) \quad (2.23)$$

with the constraints:

$$i \langle \varphi_{\kappa}(t) | \dot{\varphi}_{\kappa}(t) \rangle = g_{\kappa}(t) \quad (2.24)$$

and with g_{κ} real, but otherwise arbitrary. Later, we will choose g_{κ} such that the EOM become as simple as possible. Without restriction we may choose the initial SPFs $\varphi_{\kappa}(t=0)$ to be normalised and Eq. (2.22) then tells us that they stay normalized for all times.

We are now ready to perform the variation.

$$\dot{\Psi} = \dot{a}(t) \prod_{\kappa=1}^f \varphi_{\kappa}(q_{\kappa}, t) + a(t) \sum_{\kappa=1}^f \dot{\varphi}_{\kappa} \prod_{\nu \neq \kappa}^f \varphi_{\nu} = \dot{a}(t) \Phi + a \sum_{\kappa=1}^f \dot{\varphi}_{\kappa} \Phi^{(\kappa)} \quad (2.25)$$

$$\delta \Psi = (\delta a) \cdot \Phi + a \sum_{\kappa=1}^f (\delta \varphi_{\kappa}) \Phi^{(\kappa)} \quad (2.26)$$

where we have used the definitions

$$\Phi = \prod_{\kappa=1}^f \varphi_{\kappa} \quad \text{and} \quad \Phi^{(\kappa)} = \prod_{\substack{\nu=1 \\ \nu \neq \kappa}}^f \varphi_{\nu} \quad (2.27)$$

From the VP Eq. (2.1) follows

$$\begin{aligned} & \langle \delta a \Phi | H | a \Phi \rangle - i \langle \delta a \Phi | \dot{a} \Phi + a \sum_{\kappa} \dot{\varphi}_{\kappa} \Phi^{(\kappa)} \rangle \\ & + \sum_{\kappa=1}^f \{ \langle \delta \varphi_{\kappa} \Phi^{(\kappa)} | H | a \Phi \rangle - i \{ \langle \delta \varphi_{\kappa} \Phi^{(\kappa)} | \dot{a} \Phi + a \sum_{\kappa'} \dot{\varphi}_{\kappa'} \Phi^{(\kappa')} \} \} = 0 \end{aligned} \quad (2.28)$$

Since δa and all $\delta \varphi_{\kappa}$ are independent of each other, each line has to vanish individually.

$\delta a :$

$$(\delta a)^* a \langle \Phi | H | \Phi \rangle = i(\delta a)^* \dot{a} + i(\delta a)^* a \sum_{\kappa} \langle \Phi | \dot{\varphi}_{\kappa} \Phi^{(\kappa)} \rangle \quad (2.29)$$

Since

$$i \langle \Phi | \dot{\varphi}_{\kappa} \Phi^{(\kappa)} \rangle = i \langle \varphi_1 \cdots \varphi_{\kappa} \cdots \varphi_f | \varphi_1 \cdots \dot{\varphi}_{\kappa} \cdots \varphi_f \rangle = i \langle \varphi_{\kappa} | \dot{\varphi}_{\kappa} \rangle = g_{\kappa}, \quad (2.30)$$

follows

$$i \frac{\dot{a}}{a} = \langle \Phi | H | \Phi \rangle - \sum_{\kappa} g_{\kappa} \quad (2.31)$$

or, introducing²

$$E = \langle \Phi | H | \Phi \rangle = \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} \quad (2.32)$$

it follows

$$\boxed{i \dot{a} = (E - \sum_{\kappa} g_{\kappa}) a} \quad (2.33)$$

On the other hand, by varying a particular φ_{κ} , we obtain

$$\langle (\delta\varphi_{\kappa}) \Phi^{(\kappa)} | H | a \Phi \rangle = i \langle (\delta\varphi_{\kappa}) \Phi^{(\kappa)} | \dot{a} \Phi \rangle + i \langle (\delta\varphi_{\kappa}) \Phi^{(\kappa)} | a \sum_{\nu=1}^f \dot{\varphi}_{\nu} \Phi^{(\nu)} \rangle \quad (2.34)$$

Now

$$\begin{aligned} \langle (\delta\varphi_{\kappa}) \Phi^{(\kappa)} | H | a \Phi \rangle &= a \langle (\delta\varphi_{\kappa}) \Phi^{(\kappa)} | H | \varphi_{\kappa} \Phi^{(\kappa)} \rangle \\ &= a \langle (\delta\varphi_{\kappa}) | \langle \Phi^{(\kappa)} | H | \Phi^{(\kappa)} \rangle | \varphi_{\kappa} \rangle \\ &= a \langle (\delta\varphi_{\kappa}) | \mathcal{H}^{(\kappa)} | \varphi_{\kappa} \rangle \end{aligned} \quad (2.35)$$

with the definition

$$\mathcal{H}^{(\kappa)} = \langle \Phi^{(\kappa)} | H | \Phi^{(\kappa)} \rangle \quad (2.36)$$

$\mathcal{H}^{(\kappa)}$ is called a *mean-field*. Note that it is an operator on the κ -th degree of freedom.

The second term of the Eq. (2.34) is transformed to

$$i \langle (\delta\varphi_{\kappa}) \Phi^{(\kappa)} | \dot{a} \Phi \rangle = i \dot{a} \langle \delta\varphi_{\kappa} | \varphi_{\kappa} \rangle = a (E - \sum_{\nu=1}^f g_{\nu}) \langle \delta\varphi_{\kappa} | \varphi_{\kappa} \rangle \quad (2.37)$$

and the third term of (2.34)

$$\begin{aligned} i \langle (\delta\varphi_{\kappa}) \Phi^{(\kappa)} | a \sum_{\nu=1}^f \dot{\varphi}_{\nu} \Phi^{(\nu)} \rangle &= i a \langle \delta\varphi_{\kappa} | \dot{\varphi}_{\kappa} \rangle + i a \sum_{\nu \neq \kappa} \langle \delta\varphi_{\kappa} \varphi_{\nu} | \dot{\varphi}_{\nu} \varphi_{\kappa} \rangle \\ &= i a \langle \delta\varphi_{\kappa} | \dot{\varphi}_{\kappa} \rangle + i a \langle \delta\varphi_{\kappa} | \varphi_{\kappa} \rangle \cdot \sum_{\nu \neq \kappa} \langle \varphi_{\nu} | \dot{\varphi}_{\nu} \rangle \\ &= i a \langle \delta\varphi_{\kappa} | \dot{\varphi}_{\kappa} \rangle + a \langle \delta\varphi_{\kappa} | \varphi_{\kappa} \rangle \sum_{\nu \neq \kappa} g_{\nu} \end{aligned} \quad (2.38)$$

(2.35) = (2.37) + (2.38) divided by a :

$$\begin{aligned} \langle (\delta\varphi_{\kappa}) | \mathcal{H}^{(\kappa)} | \varphi_{\kappa} \rangle &= \\ (E - \sum_{\nu=1}^f g_{\nu}) \langle \delta\varphi_{\kappa} | \varphi_{\kappa} \rangle &+ i \langle \delta\varphi_{\kappa} | \dot{\varphi}_{\kappa} \rangle + \sum_{\nu \neq \kappa} g_{\nu} \langle \delta\varphi_{\kappa} | \varphi_{\kappa} \rangle \end{aligned} \quad (2.39)$$

or

$$i \langle \delta\varphi_{\kappa} | \dot{\varphi}_{\kappa} \rangle = \langle \delta\varphi_{\kappa} | \mathcal{H}^{(\kappa)} | \varphi_{\kappa} \rangle - (E - g_{\kappa}) \langle \delta\varphi_{\kappa} | \varphi_{\kappa} \rangle \quad (2.40)$$

²Note $E = E(t)$ in general.

Since $\delta\varphi_\kappa$ is arbitrary, we finally arrive at

$$\boxed{\begin{aligned} i \dot{\varphi}_\kappa &= (\mathcal{H}^{(\kappa)} - E + g_\kappa) \varphi_\kappa \\ i \dot{a} &= (E - \sum_{\kappa=1}^f g_\kappa) a \end{aligned}} \quad (2.41)$$

Everything may be time-dependent.

If we multiply the first of the EOMs by $\langle \varphi_\kappa |$ we see that the constraint is obeyed (of course!),

$$i \langle \varphi_\kappa | \dot{\varphi}_\kappa \rangle = \langle \varphi_\kappa | \mathcal{H}^{(\kappa)} | \varphi_\kappa \rangle - E + g_\kappa = g_\kappa \quad (2.42)$$

because

$$\langle \varphi_\kappa | \mathcal{H}^{(\kappa)} | \varphi_\kappa \rangle = \langle \varphi_\kappa | \Phi^{(\kappa)} | H | \varphi_\kappa | \Phi^{(\kappa)} \rangle = \langle \Phi | H | \Phi \rangle = E \quad (2.43)$$

We now have to decide what to take for g_κ . Remember that we can choose *any* function $g_\kappa(t)$ as long as it is real. The simplest choice is $g_\kappa \equiv 0$. This yields:

$$\boxed{\begin{aligned} a(t) &= a(0) \cdot \exp\left(-i \int_0^t E(t') dt'\right) \\ i \dot{\varphi}_\kappa &= (\mathcal{H}^{(\kappa)} - E) \varphi_\kappa \\ &= (1 - |\varphi_\kappa\rangle\langle\varphi_\kappa|) \mathcal{H}^{(\kappa)} \varphi_\kappa \end{aligned}} \quad (2.44)$$

The very last line is introduced because of its similarity with the MCTDH EOM. It holds because of (2.43).

For hermitian time-independent Hamiltonians the Dirac-Frenkel variational principle ensures that the norm and the mean energy of the WP is conserved. Hence $E(t)$ is real and time-independent. For hermitian time-dependent Hamiltonians E will become time-dependent but stays real. For non-hermitian Hamiltonians E will become both complex and time-dependent.

Hence for hermitian Hamiltonians there are two other meaningful choices for g_κ , namely

$$g_\kappa = E \quad (2.45)$$

and

$$g_\kappa = E/f \quad (2.46)$$

Then³

$$\boxed{\begin{aligned} a(t) &= a(0) \cdot \exp\left(i(f-1) \int_0^t E(t') dt'\right) \\ i \dot{\varphi}_\kappa &= \mathcal{H}^{(\kappa)} \varphi_\kappa \end{aligned}} \quad (2.47)$$

³The TDH solution Ψ is always the same, only its representation differs.

and

$$\boxed{\begin{aligned} a(t) &= a(0) \\ i\dot{\varphi}_\kappa &= \left(\mathcal{H}^{(\kappa)} - \left(\frac{f-1}{f} \right) E(t) \right) \varphi_\kappa \end{aligned}} \quad (2.48)$$

Hence the various choices of g_κ merely shift phase-factors from a to φ_κ and vice-versa.

The derivation of the EOM of the TDH method is now concluded.

The TDH solution is approximate because of the very restricted form of the wavefunction. To investigate the quality of a TDH solution, we adopt the idea of an effective Hamiltonian:

$$i\dot{\Psi} = H_{\text{eff}} \Psi \quad (2.49)$$

where Ψ denotes the TDH solution.

Using the last set of EOMs and remembering (since $\dot{a} = 0$ there)

$$\dot{\Psi} = a \sum_{\kappa} \dot{\varphi} \Phi^{(\kappa)} \quad (2.50)$$

one readily finds⁴

$$\boxed{H_{\text{eff}} = \sum_{\kappa=1}^f \mathcal{H}^{(\kappa)} - (f-1) E} \quad (2.51)$$

The TDH solution is the exact solution of the TDSE using H_{eff} as Hamiltonian. To proceed, we split the Hamiltonian into separable and non-separable terms.

$$H = \sum_{\kappa=1}^f h^{(\kappa)} + V \quad (2.52)$$

where $h^{(\kappa)}$ operates only on the κ -th degree of freedom.

Example:

$$H = -\frac{1}{2m} \frac{\partial^2}{\partial x_1^2} - \frac{1}{2m} \frac{\partial^2}{\partial x_2^2} + \frac{1}{2} m\omega_1^2 x_1^2 + \frac{1}{2} m\omega_2^2 x_2^2 + \lambda x_1^2 x_2^2 \quad (2.53)$$

$$\begin{aligned} h^{(1)}(x_1) &= -\frac{1}{2m} \frac{\partial^2}{\partial x_1^2} + \frac{1}{2} m\omega_1^2 x_1^2 \\ h^{(2)}(x_2) &= -\frac{1}{2m} \frac{\partial^2}{\partial x_2^2} + \frac{1}{2} m\omega_2^2 x_2^2 \\ V(x_1, x_2) &= \lambda x_1^2 x_2^2 \end{aligned} \quad (2.54)$$

⁴Everything may be time-dependent.

The mean-fields and the effective Hamiltonian can now be evaluated somewhat more explicitly

$$\begin{aligned}\mathcal{H}^{(\kappa)} &= \langle \Phi^{(\kappa)} | H | \Phi^{(\kappa)} \rangle \\ &= h^{(\kappa)} \langle \Phi^{(\kappa)} | \Phi^{(\kappa)} \rangle + \sum_{\nu \neq \kappa} \langle \Phi^{(\kappa)} | h^{(\nu)} | \Phi^{(\kappa)} \rangle + \langle \Phi^{(\kappa)} | V | \Phi^{(\kappa)} \rangle\end{aligned}\quad (2.55)$$

or more compactly

$$\mathcal{H}^{(\kappa)} = h^{(\kappa)} + \sum_{\nu \neq \kappa} E_{\text{uncorr}}^{(\nu)} + v^{(\kappa)} \quad (2.56)$$

with

$$E_{\text{uncorr}}^{(\nu)} = \langle \Phi^{(\kappa)} | h^{(\nu)} | \Phi^{(\kappa)} \rangle = \langle \varphi^{(\nu)} | h^{(\nu)} | \varphi^{(\nu)} \rangle \quad (2.57)$$

$$E_{\text{uncorr}} = \langle \Phi | \sum_{\nu} h^{(\nu)} | \Phi \rangle = \sum_{\nu} E_{\text{uncorr}}^{(\nu)} \quad (2.58)$$

and

$$E_{\text{corr}} = \langle \Phi | V | \Phi \rangle = \frac{\langle \Psi | V | \Psi \rangle}{\langle \Psi | \Psi \rangle} \quad (2.59)$$

Hence

$$E = \langle \Phi | H | \Phi \rangle = E_{\text{uncorr}} + E_{\text{corr}} \quad (2.60)$$

Before we continue, it may be helpful to give an example for $v^{(\kappa)}$,

$$v^{(1)}(x_1) = \langle \varphi_2 \cdots \varphi_f | V(x_1, \dots, x_f) | \varphi_2 \cdots \varphi_f \rangle \quad (2.61)$$

For the 2D case it reads

$$v^{(1)}(x_1) = \int |\varphi_2(x_2)|^2 V(x_1, x_2) dx_2 \quad (2.62)$$

i.e. one averages the potential over the "other" degree of freedom. For the specific case

$$V = \lambda x_1^2 x_2^2 \quad (2.63)$$

one obtains

$$v^{(1)}(x_1) = \lambda x_1^2 \langle \varphi_2 | x_2^2 | \varphi_2 \rangle \quad (2.64)$$

which demonstrates that a product form leads to a great simplification!

We had derived the equation for the mean-fields

$$\mathcal{H}^{(\kappa)} = h^{(\kappa)} + v^{(\kappa)} + E_{\text{uncorr}} - E_{\text{uncorr}}^{(\kappa)} = h^{(\kappa)} + v^{(\kappa)} + \sum_{\nu \neq \kappa} E_{\text{uncorr}}^{(\nu)} \quad (2.65)$$

$$\sum_{\kappa=1}^f \mathcal{H}^{(\kappa)} = \sum_{\kappa=1}^f (h^{(\kappa)} + v^{(\kappa)}) + (f-1) E_{\text{uncorr}} \quad (2.66)$$

$$H_{\text{eff}} = \sum_{\kappa=1}^f \mathcal{H}^{(\kappa)} - (f-1) E = \sum_{\kappa=1}^f (h^{(\kappa)} + v^{(\kappa)}) - (f-1) E_{\text{corr}} \quad (2.67)$$

and

$$H - H_{\text{eff}} = V - \sum_{\kappa=1}^f v^{(\kappa)} + (f-1) E_{\text{corr}} \quad (2.68)$$

This makes it clear that TDH is exact, *i.e.* $H = H_{\text{eff}}$, if $V \equiv 0$. In other words, if the Hamiltonian is separable.

To illuminate the errors introduced by TDH, let us consider a simple 2D example.

$$H = h^{(1)} + h^{(2)} + v_1(x_1) \cdot v_2(x_2) \quad (2.69)$$

$$E_{\text{corr}} = \langle \varphi_1 | v_1 | \varphi_1 \rangle \cdot \langle \varphi_2 | v_2 | \varphi_2 \rangle \equiv \langle v_1 \rangle \langle v_2 \rangle \quad (2.70)$$

$$v^{(1)}(x_1) = v_1(x_1) \cdot \langle v_2 \rangle \quad (2.71)$$

$$v^{(2)}(x_2) = v_2(x_2) \cdot \langle v_1 \rangle \quad (2.72)$$

$$H - H_{\text{eff}} = v_1 v_2 - v_2 \langle v_1 \rangle - v_1 \langle v_2 \rangle + \langle v_1 \rangle \langle v_2 \rangle \quad (2.73)$$

$$\boxed{H - H_{\text{eff}} = (v_1 - \langle v_1 \rangle)(v_2 - \langle v_2 \rangle)} \quad (2.74)$$

Hence the TDH-error is small, if the potential varies only little over the width of the wavepacket. In the (semi-)classical limit, when the wavefunction becomes a δ -function, TDH becomes exact! Quantum mechanics is so complicated because it is non-local.

In realistic applications, it is often the hard repulsion which limits the accuracy of TDH. This is demonstrated in Fig. 2.1. If the wave packet is close to the potential minimum, $v - \langle v \rangle$ takes only small values as indicated by the arrow on the right hand side. Close to the strongly repulsive wall, however $v - \langle v \rangle$ varies appreciably as the right hand side of the WP sees a much lower potential than its left hand side. Remember, however, that the TDH errors are caused by the non-separable parts of the Hamiltonians only. A separable strongly repulsive wall would not introduce TDH errors.

TDH reduces an f -dimensional PDE to a set of f one-dimensional PDE. That is an enormous simplification. Assume we have 20 basis functions per DOF and 12 degrees of freedom. Then there are $20^{12} = 4 \cdot 10^{15}$ coupled differential equations to be solved for the standard method but only $12 \cdot 20 = 240$ equations for TDH. The first problem is undoable, the latter very simple. Well, it would be very simple if there wouldn't be the integral problem.

At each time-step one has to evaluate the mean-fields $v^{(\kappa)}$ which are $(f-1)$ dimensional integrals

$$v^{(1)}(x_1) = \int |\phi^{(1)}(x_2, \dots, x_f)|^2 V(x_1, \dots, x_f) dx_2 \cdots dx_f \quad (2.75)$$

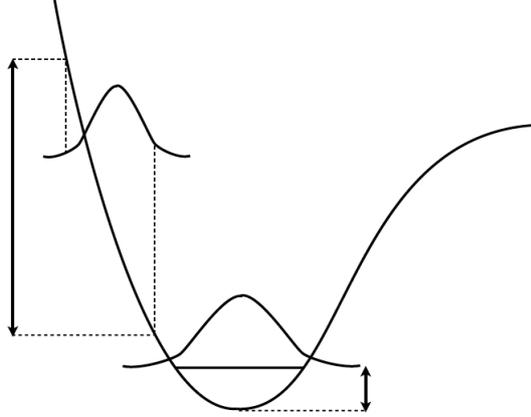


Figure 2.1: Visualization of $v - \langle v \rangle$. The arrows indicate the variation of the potential energy over the range of the wave packet.

If one would do these integrals directly, one would have to run f -times over the full product grid, which is undoable. One way out is to write the potential in product form

$$V(x_1, \dots, x_f) = \sum_{r=1}^s v_{1,r}(x_1) \cdots v_{f,r}(x_f) \quad (2.76)$$

Then

$$v^{(1)}(x_1) = \sum_{r=1}^s v_{1,r}(x_1) \cdot \langle v_{2,r} \rangle \cdots \langle v_{f,r} \rangle \quad (2.77)$$

To do all the integral one has to run over $s \cdot f \cdot N$ grid points. If s is, say 1000, then we have for our example $1000 \times 12 \times 20 = 240,000$ operations, which is easily doable. A method, called *potfit*, which transforms a general potential to product form will be discussed later in more detail.

Chapter 3

The Multiconfiguration Time Dependent Hartree Method

3.1 MCTDH fundamentals

To overcome the limitations of TDH, we turn to a multi-configurational ansatz and write the WF as

$$\Psi(q_1, \dots, q_f, t) = \sum_{j_1}^{n_1} \cdots \sum_{j_f}^{n_f} A_{j_1 \dots j_f}(t) \prod_{\kappa=1}^f \varphi_{j_\kappa}^{(\kappa)}(q_\kappa, t) \quad (3.1)$$

As in TDH, this ansatz is not unique. One may perform linear transformations among the SPFs (orbitals) and the inverse transformations on the coefficients (A-vector).

$$\begin{aligned} \tilde{\varphi}_{j_\kappa}^{(\kappa)} &= \sum_{l_\kappa} U_{j_\kappa l_\kappa}^{(\kappa)} \varphi_{l_\kappa}^{(\kappa)} \\ \tilde{A}_{j_1 \dots j_f} &= \sum_{l_1 \dots l_f} A_{l_1 \dots l_f} (U^{(1)})_{l_1 j_1}^{-1} \cdots (U^{(f)})_{l_f j_f}^{-1} \end{aligned} \quad (3.2)$$

then

$$\Psi = \sum_{j_1 \dots j_f} \tilde{A}_{j_1 \dots j_f} \tilde{\varphi}_{j_1} \cdots \tilde{\varphi}_{j_f} \quad (3.3)$$

As in TDH we need constraints to lift the ambiguity. As constraints we choose

$$i \langle \varphi_l^{(\kappa)} | \dot{\varphi}_j^{(\kappa)} \rangle = \langle \varphi_l^{(\kappa)} | \hat{g}^{(\kappa)} | \varphi_j^{(\kappa)} \rangle \quad (3.4)$$

with some arbitrary constraint operator $\hat{g}^{(\kappa)}$. The operator $\hat{g}^{(\kappa)}$ defines the transformation matrix $U^{(\kappa)}$. In fact, after the equations of motion are derived one can show

$$i \dot{U}^{(\kappa)} = \mathbf{g}^{(\kappa)T} U^{(\kappa)} \quad (3.5)$$

where

$$(\mathbf{g}^{(\kappa)})_{lj} = \langle \varphi_l^{(\kappa)} | \hat{g}^{(\kappa)} | \varphi_j^{(\kappa)} \rangle \quad (3.6)$$

A formal solution is hence

$$\mathbf{U}^{(\kappa)}(t) = \mathcal{T} \exp\left(-i \int_0^t \mathbf{g}^{(\kappa)T}(t') dt'\right) \quad (3.7)$$

where \mathcal{T} is the time-ordering operator, and $\mathbf{U}^{(\kappa)}$ is the transformation matrix from the SPFs computed with $\hat{g}^{(\kappa)} \equiv 0$ to those computed with $\hat{g}^{(\kappa)}$.

It is, of course, of great advantage if the SPFs are orthonormal. Orthonormality of the SPFs is not a restriction as one can always find a transformation $\mathbf{U}^{(\kappa)}$ which orthogonalizes the SPFs. The overlap matrix is given by (dropping κ for the sake of simplicity)

$$S_{lj} = \langle \varphi_l | \varphi_j \rangle \quad (3.8)$$

and

$$\dot{S}_{lj} = \langle \dot{\varphi}_l | \varphi_j \rangle + \langle \varphi_l | \dot{\varphi}_j \rangle = -i (g_{lj} - g_{jl}^*) = -i (\mathbf{g} - \mathbf{g}^\dagger)_{lj}$$

Hence

$$\dot{\mathbf{S}} = 0 \quad \text{if} \quad \mathbf{g} = \mathbf{g}^\dagger \quad (3.9)$$

and thus we require hermitian constraint operators.

If the initial WF, $\Psi(0)$, has orthonormal SPFs

$$S_{lj}^{(\kappa)}(0) = \langle \varphi_l^{(\kappa)}(0) | \varphi_j^{(\kappa)}(0) \rangle = \delta_{lj} \quad (3.10)$$

then it follows that the SPFs stay orthonormal for all times, because $\dot{\mathbf{S}}^{(\kappa)} = 0$ and hence $\mathbf{S}^{(\kappa)}(t) = \mathbf{1}$.

Before we derive the MCTDH equations of motion we have to introduce some notation:

- Composite indices:

$$J \equiv (j_1, \dots, j_f)$$

$$A_J \equiv A_{j_1 \dots j_f}$$

- Configuration or Hartree product:

$$\Phi_J \equiv \prod_{\kappa=1}^f \varphi_{j_\kappa}^{(\kappa)}$$

Next we introduce single-hole functions. The WF Ψ lies, of course, in the space spanned by the SPFs and we can make use of completeness

$$\Psi = \sum_{l=1}^{n_\kappa} |\varphi_l^{(\kappa)}\rangle \langle \varphi_l^{(\kappa)} | \Psi \rangle_\kappa = \sum_{l=1}^{n_\kappa} \varphi_l^{(\kappa)} \Psi_l^{(\kappa)} \quad (3.11)$$

To make this clear, we write the single-hole function $\Psi_l^{(\kappa)}$ for the first DOF $\kappa = 1$

$$\Psi_l^{(1)} = \langle \varphi_l^{(1)} | \Psi \rangle \sum_{j_2=1}^{n_2} \dots \sum_{j_f=1}^{n_f} A_{lj_2 \dots j_f} \varphi_{j_2}^{(2)} \dots \varphi_{j_f}^{(f)} \quad (3.12)$$

For a general definition, we need an extended nomenclature:

- $J^\kappa \equiv (j_1, \dots, j_{\kappa-1}, j_{\kappa+1}, \dots, j_f)$
- $J_l^\kappa \equiv (j_1, \dots, j_{\kappa-1}, l, j_{\kappa+1}, \dots, j_f)$
- $\Phi_{J^\kappa} \equiv \prod_{\substack{\nu=1 \\ \nu \neq \kappa}}^f \varphi_{j_\nu}^{(\nu)}$

Then

$$\Psi_l^{(\kappa)} = \sum_{J^\kappa} A_{J_l^\kappa} \Phi_{J^\kappa} \quad (3.13)$$

The single-hole functions allow us to introduce mean-fields

$$\langle H \rangle_{jl}^{(\kappa)} = \langle \Psi_j^{(\kappa)} | H | \Psi_l^{(\kappa)} \rangle \quad (3.14)$$

Note that we have not only one mean-field for each degree of freedom, but a matrix of mean-fields!

Next, we introduce the density matrix¹

$$\rho_{kl}^{(\kappa)} = \langle \Psi_k^{(\kappa)} | \Psi_l^{(\kappa)} \rangle = \sum_{J^\kappa} A_{J_k^\kappa}^* A_{J_l^\kappa} \quad (3.15)$$

Note that

$$\langle \Psi | \Psi \rangle = \sum_J A_J^* A_J = \|\mathbf{A}\|^2 \quad (3.16)$$

because of the orthonormality of the SPFs. Hence

$$\text{Tr} [\rho^{(\kappa)}] = \sum_{j=1}^{n_\kappa} \rho_{jj}^{(\kappa)} = \|\Psi\|^2 \quad (3.17)$$

We are now ready to derive the MCTDH-EOM. But before that we will make some remarks on densities.

3.2 Remarks on densities

The density matrix of a mixed state reads

$$\hat{\rho} = \sum_n p_n |\Psi_n\rangle \langle \Psi_n|$$

where $p_n \geq 0$ denote probabilities.

And of a pure state is given by:

$$\hat{\rho} = |\Psi\rangle \langle \Psi|$$

¹According to the extended notation:

$$\rho_{kl}^{(\kappa)} = \sum_{J^\kappa} A_{J_k^\kappa}^* A_{J_l^\kappa} = \sum_{J^\kappa} A_{j_1, \dots, j_{\kappa-1}, k, j_{\kappa+1}, \dots, j_f}^* A_{j_1, \dots, j_{\kappa-1}, l, j_{\kappa+1}, \dots, j_f}$$

A reduced density is obtained by tracing out unwanted DOFs

$$\hat{\rho}_{\text{red}} = \text{Trace}_{\text{unwanted dofs}} \{ |\Psi\rangle\langle\Psi| \}$$

and the trace of an operator is given by

$$\text{Trace} \{ \hat{A} \} = \sum_n \langle n | \hat{A} | n \rangle$$

for *any* complete orthonormal basis $|n\rangle$.

Choosing $|x\rangle$ as basis one obtains the one-particle reduced densities

$$\hat{\rho}_{\text{red}}^{(\kappa)}(q_\kappa, q'_\kappa) = \int \Psi(q_1 \cdots q_\kappa \cdots q_f) \Psi^*(q_1 \cdots q'_\kappa \cdots q_f) dq_1 \cdots dq_{\kappa-1} dq_{\kappa+1} \cdots dq_f$$

and

$$\begin{aligned} \langle \varphi_j^{(\kappa)} | \hat{\rho}_{\text{red}}^{(\kappa)} | \varphi_l^{(\kappa)} \rangle &= \int \varphi_j^{(\kappa)*} \Psi \Psi^* \varphi_l^{(\kappa)} dq_\kappa dq'_\kappa dq_1 \cdots dq_{\kappa-1} dq_{\kappa+1} \cdots dq_f \\ &= \int \Psi_j^{(\kappa)} \Psi_l^{(\kappa)*} dq_1 \cdots dq_{\kappa-1} dq_{\kappa+1} \cdots dq_f \\ &= \langle \Psi_l^{(\kappa)} | \Psi_j^{(\kappa)} \rangle = \rho_{lj}^{\text{MCTDH}} \end{aligned} \quad (3.18)$$

Hence

$$(\rho_{\text{red}}^{(\kappa)}) = (\rho_{\text{MCTDH}}^{(\kappa)})^T \quad (3.19)$$

The diagonal values, $q_\kappa = q'_\kappa$, of the reduced density are given by

$$\rho^{(\kappa)}(q_\kappa, q_\kappa) \equiv \rho^{(\kappa)}(q_\kappa) = \int |\Psi(q_1 \cdots q_f)|^2 dq_1 \cdots dq_{\kappa-1} dq_{\kappa+1} \cdots dq_f \quad (3.20)$$

This we plot very often. The data is stored on the MCTDH `gridpop` file. Similarly, we can define 2-particle densities. Diagonal 2-particle densities can be plotted with `showsys`.²

3.3 MCTDH Equations of Motion

To derive the MCTDH-EOM, we first repeat the MCTDH ansatz for the wave function

$$\begin{aligned} \Psi(q_1, \dots, q_f, t) &= \sum_{j_1}^{n_1} \cdots \sum_{j_f}^{n_f} A_{j_1 \dots j_f}(t) \varphi_{j_1}^{(1)}(q_1, t) \cdots \varphi_{j_f}^{(f)}(q_f, t) \\ &= \sum_J A_J \Phi_J = \sum_{j=1}^{n_\kappa} \varphi_j^{(\kappa)} \Psi_j^{(\kappa)} \end{aligned} \quad (3.21)$$

The variation with respect to coefficients and SPFs yields configurations and single-hole functions, respectively

$$\frac{\delta \Psi}{\delta A_J} = \Phi_J \quad (3.22)$$

²For Hartree one can give the wavefunction for the κ -th degree, $\varphi_\kappa(q_\kappa, t)$, but for any correlated WF this is no longer possible. For correlated WF one can only inspect the reduced densities.

$$\frac{\delta\Psi}{\delta\varphi_j^{(\kappa)}} = \Psi_j^{(\kappa)} \quad (3.23)$$

And the time derivation is given by

$$\dot{\Psi} = \sum_J \dot{A}_J \Phi_J + \sum_{\kappa=1}^f \sum_{j=1}^{n_\kappa} \dot{\varphi}_j^{(\kappa)} \Psi_j^{(\kappa)} \quad (3.24)$$

We first consider variations with respect to the coefficients only

$$\begin{aligned} \delta A_J : \\ \langle \delta\Psi | H | \Psi \rangle &= \langle \Phi_J | H | \Psi \rangle = \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L \\ &\stackrel{DFVP}{=} i \langle \delta\Psi | \dot{\Psi} \rangle \\ &= i \langle \Phi_J | \dot{\Psi} \rangle \\ &= i \sum_L \langle \Phi_J | \dot{A}_L \Phi_L \rangle + i \sum_{\kappa} \sum_l \langle \Phi_J | \dot{\varphi}_l^{(\kappa)} \Psi_l^{(\kappa)} \rangle \\ &= i \dot{A}_J + i \sum_{\kappa} \sum_l \langle \varphi_{j_\kappa}^{(\kappa)} | \dot{\varphi}_l^{(\kappa)} \rangle \langle \Phi_{J_\kappa} | \Psi_l^{(\kappa)} \rangle \\ &= i \dot{A}_J + i \sum_{\kappa} \sum_l (-i g_{j_\kappa l}^{(\kappa)}) A_{J_l^\kappa} \end{aligned} \quad (3.25)$$

Solving for \dot{A} yields

$$\boxed{i \dot{A}_J = \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L - i \sum_{\kappa=1}^f \sum_{l=1}^{n_\kappa} g_{j_\kappa l}^{(\kappa)} A_{J_l^\kappa}} \quad (3.26)$$

which holds because

$$g_{j_\kappa l}^{(\kappa)} \equiv \langle \varphi_{j_\kappa}^{(\kappa)} | \hat{g}^{(\kappa)} | \varphi_l^{(\kappa)} \rangle = i \langle \varphi_{j_\kappa}^{(\kappa)} | \dot{\varphi}_l^{(\kappa)} \rangle \quad (3.27)$$

and

$$\langle \Phi_{J_\kappa} | \Psi_l^{(\kappa)} \rangle = \sum_{L^\kappa} \langle \Phi_{J_\kappa} | A_{L_l^\kappa} \Phi_{L^\kappa} \rangle = A_{J_l^\kappa} \quad (3.28)$$

Next we consider variations with respect to the SPFs.

$$\begin{aligned} \delta\varphi_j^{(\kappa)} : \\ \langle \delta\Psi | H | \Psi \rangle &= \langle \Psi_j^{(\kappa)} | H | \Psi \rangle = \langle \Psi_j^{(\kappa)} | H | \sum_l \Psi_l^{(\kappa)} \varphi_l^{(\kappa)} \rangle \\ &= \sum_{l=1}^{n_\kappa} \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} \stackrel{DFVP}{=} i \langle \delta\Psi | \dot{\Psi} \rangle \\ &= \underbrace{i \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle \dot{A}_L}_{\text{part 1}} + \underbrace{i \sum_L \langle \Psi_j^{(\kappa)} | \sum_{\nu=1}^f \sum_{l=1}^{n_\nu} \dot{\varphi}_l^{(\nu)} \Psi_l^{(\nu)} \rangle}_{\text{part 2}} \end{aligned} \quad (3.29)$$

For the sake of simplicity we postpone the discussion of the general case to later and set $\hat{g}^{(\kappa)} \equiv 0$ in the following. Then

$$i\dot{A}_L = \langle \Phi_L | H | \Psi \rangle = \sum_K \langle \Phi_L | H | \Phi_K \rangle A_K \quad (3.30)$$

and Eq. (3.29) part 1 reads

$$i \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle \dot{A}_L = \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle \langle \Phi_L | H | \Psi \rangle \quad (3.31)$$

which with

$$\Phi_L = \Phi_{L^\kappa} \varphi_{l^\kappa}^{(\kappa)} \quad (3.32)$$

and

$$\Psi_j^{(\kappa)} = \sum_{J^\kappa} A_{J_j^\kappa} \Phi_{J^\kappa} \quad (3.33)$$

can be turned into

$$(\text{part1}) = \sum_{L^\kappa, l^\kappa} A_{L_j^\kappa}^* |\varphi_{l^\kappa}^{(\kappa)}\rangle \langle \varphi_{l^\kappa}^{(\kappa)} | \Phi_{L^\kappa} | H | \Psi \rangle = P^{(\kappa)} \langle \Psi_j^{(\kappa)} | H | \Psi \rangle \quad (3.34)$$

where we have introduced the MCTDH projector

$$P^{(\kappa)} = \sum_{j=1}^{n_\kappa} |\varphi_j^{(\kappa)}\rangle \langle \varphi_j^{(\kappa)}| \quad (3.35)$$

Hence for part 1 of Eq. (3.29) we arrive at

$$i \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle \dot{A}_L = P^{(\kappa)} \langle \Psi_j^{(\kappa)} | H | \Psi \rangle = P^{(\kappa)} \sum_{l=1}^{n_\kappa} \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} \quad (3.36)$$

Next we turn to part 2 of Eq. (3.29)

$$i \langle \Psi_j^{(\kappa)} | \sum_{\nu=1}^f \sum_{l=1}^{n_\nu} \dot{\varphi}_l^{(\nu)} \Psi_l^{(\nu)} \rangle = i \langle \Psi_j^{(\kappa)} | \sum_l \dot{\varphi}_l^{(\kappa)} \Psi_l^{(\kappa)} \rangle = i \sum_l \rho_{jl}^{(\kappa)} \dot{\varphi}_l^{(\kappa)} \quad (3.37)$$

Here we have used

$$\langle \varphi_j^{(\kappa)} | \dot{\varphi}_l^{(\kappa)} \rangle = 0 \quad (3.38)$$

which holds for any j and l because $\hat{g}^{(\kappa)} \equiv 0$ is assumed. Only when $\nu = \kappa$ there is no SPF with which $\dot{\varphi}$ is to be overlapped.

Putting all parts of Eq. 3.29 together, we have

$$\sum_{l=1}^{n_\kappa} \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} = P^{(\kappa)} \sum_{l=1}^{n_\kappa} \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} + i \sum_l \rho_{jl}^{(\kappa)} \dot{\varphi}_l^{(\kappa)} \quad (3.39)$$

or

$$i \dot{\varphi}_j^{(\kappa)} = \sum_{k,l} (\boldsymbol{\rho}^{(\kappa)^{-1}})_{jl} (1 - P^{(\kappa)}) \langle H \rangle_{lk}^{(\kappa)} \varphi_k^{(\kappa)} \quad (3.40)$$

Hence for $\hat{g}^{(\kappa)} \equiv 0$ we have the following set of EOM:

$$\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L \\ i\dot{\varphi}_j^{(\kappa)} &= (1 - P^{(\kappa)}) \sum_{k,l=1}^{n_\kappa} (\boldsymbol{\rho}^{(\kappa)^{-1}})_{jl} \langle \mathbf{H} \rangle_{lk}^{(\kappa)} \varphi_k^{(\kappa)} \end{aligned} \quad (3.41)$$

Introducing vectors of SPFs

$$\boldsymbol{\varphi}^{(\kappa)} = (\varphi_1^{(\kappa)} \dots \varphi_{n_\kappa}^{(\kappa)})^T \quad (3.42)$$

we can write the last equation more compactly

$$i\dot{\boldsymbol{\varphi}}^{(\kappa)} = (1 - P^{(\kappa)}) \boldsymbol{\rho}^{(\kappa)^{-1}} \langle \mathbf{H} \rangle^{(\kappa)} \boldsymbol{\varphi}^{(\kappa)} \quad (3.43)$$

In full generality the EOM read

$$\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L - \sum_{\kappa=1}^f \sum_{l=1}^{n_\kappa} g_{j,\kappa l}^{(\kappa)} A_{J_l^\kappa} \\ i\dot{\boldsymbol{\varphi}}^{(\kappa)} &= (\hat{g}^{(\kappa)} \mathbf{1}) \boldsymbol{\varphi}^{(\kappa)} + (1 - P^{(\kappa)}) \{ \boldsymbol{\rho}^{(\kappa)^{-1}} \langle \mathbf{H} \rangle^{(\kappa)} - \hat{g}^{(\kappa)} \mathbf{1} \} \boldsymbol{\varphi}^{(\kappa)} \end{aligned} \quad (3.44)$$

The last equation may be written as

$$i\dot{\boldsymbol{\varphi}}^{(\kappa)} = P^{(\kappa)} \hat{g}^{(\kappa)} \boldsymbol{\varphi}^{(\kappa)} + (1 - P^{(\kappa)}) \boldsymbol{\rho}^{(\kappa)^{-1}} \langle \mathbf{H} \rangle^{(\kappa)} \boldsymbol{\varphi}^{(\kappa)} \quad (3.45)$$

or

$$i\dot{\boldsymbol{\varphi}}^{(\kappa)} = \{ \mathbf{g}^{(\kappa)T} + (1 - P^{(\kappa)}) \boldsymbol{\rho}^{(\kappa)^{-1}} \langle \mathbf{H} \rangle^{(\kappa)} \} \boldsymbol{\varphi}^{(\kappa)} \quad (3.46)$$

As

$$\begin{aligned} P^{(\kappa)} \hat{g}^{(\kappa)} \varphi_j^{(\kappa)} &= \sum_l |\varphi_l^{(\kappa)}\rangle \langle \varphi_l^{(\kappa)} | \hat{g}^{(\kappa)} | \varphi_j^{(\kappa)}\rangle \\ &= \sum_l |\varphi_l^{(\kappa)}\rangle g_{lj}^{(\kappa)} \\ &= g_{lj}^{(\kappa)} \varphi_l^{(\kappa)} = (\mathbf{g}^T \boldsymbol{\varphi})_j \end{aligned} \quad (3.47)$$

Defining

$$H_R = H - \sum_{\kappa} \hat{g}^{(\kappa)} \quad (3.48)$$

one arrives at the EOM

$$\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H_R | \Phi_L \rangle A_L \\ i\dot{\boldsymbol{\varphi}}^{(\kappa)} &= \{ \hat{g}^{(\kappa)} \mathbf{1} + (1 - P^{(\kappa)}) \boldsymbol{\rho}^{(\kappa)^{-1}} \langle \mathbf{H}_R \rangle \} \boldsymbol{\varphi}^{(\kappa)} \end{aligned} \quad (3.49)$$

Hence the two most obvious choices for constraint operator are either

$$\hat{g}^{(\kappa)} \equiv 0 \quad (3.50)$$

or

$$\hat{g}^{(\kappa)} = h^{(\kappa)} \quad (3.51)$$

where

$$H = \sum_{\kappa} h^{(\kappa)} + H_R \quad (3.52)$$

i.e. the $\sum h^{(\kappa)}$ term stands for the separable part of H , and H_R for the non-separable or residual part.

To prove Eq. (3.49), we note:

$$\langle \Phi_J | H | \Phi_L \rangle = \langle \Phi_J | H_R + \sum_{\kappa} \hat{g}^{(\kappa)} | \Phi_L \rangle = \langle \Phi_J | H_R | \Phi_L \rangle + \sum_{\kappa} \hat{g}_{j\kappa l\kappa}^{(\kappa)} \delta_{J\kappa L\kappa} \quad (3.53)$$

where the last term cancels the last term of the $i\dot{A}$ equation. And similarly

$$\begin{aligned} \langle H \rangle_{jl}^{(\kappa)} &= \langle H_R + \sum_{\kappa} g^{(\kappa)} \rangle_{jl}^{(\kappa)} \\ &= \langle \Psi_j^{(\kappa)} | g^{(\kappa)} | \Psi_l^{(\kappa)} \rangle + \sum_{\nu \neq \kappa} \langle \Psi_j^{(\kappa)} | g^{(\nu)} | \Psi_l^{(\kappa)} \rangle + \langle H_R \rangle_{jl}^{(\kappa)} \\ &= \hat{g}^{(\kappa)} \rho_{jl}^{(\kappa)} + \epsilon_{jl} + \langle H_R \rangle_{jl}^{(\kappa)} \end{aligned} \quad (3.54)$$

which defines the matrix ϵ_{jl} . The EOM for the SPF hence reads

$$\begin{aligned} i\dot{\varphi}^{(\kappa)} &= \hat{g}^{(\kappa)} \varphi^{(\kappa)} + (1 - P^{(\kappa)}) \{ \rho^{-1} [\langle \mathbf{H}_R \rangle^{(\kappa)} + \epsilon + \hat{g}^{(\kappa)} \rho] - g^{(\kappa)} \} \varphi^{(\kappa)} \\ &= \hat{g}^{(\kappa)} \varphi^{(\kappa)} + (1 - P^{(\kappa)}) \rho^{-1} \langle \mathbf{H}_R \rangle^{(\kappa)} \varphi^{(\kappa)} \end{aligned} \quad (3.55)$$

as $\epsilon \varphi^{(\kappa)}$ is annihilated by the projector $(1 - P^{(\kappa)})$.

With the arguments just given (replacing $\hat{g}^{(\kappa)}$ with $h^{(\kappa)}$), we find for $\hat{g}^{(\kappa)} \equiv 0$

$$\boxed{\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L \\ i\dot{\varphi}^{(\kappa)} &= (1 - P^{(\kappa)}) \{ h^{(\kappa)} \mathbf{1} + \rho^{(\kappa)-1} \langle \mathbf{H}_R \rangle \} \varphi^{(\kappa)} \end{aligned}} \quad (3.56)$$

whereas for $\hat{g}^{(\kappa)} = h^{(\kappa)}$ we arrive at

$$\boxed{\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H_R | \Phi_L \rangle A_L \\ i\dot{\varphi}^{(\kappa)} &= \{ h^{(\kappa)} \mathbf{1} + (1 - P^{(\kappa)}) \langle \mathbf{H}_R \rangle \} \varphi^{(\kappa)} \end{aligned}} \quad (3.57)$$

In the MCTDH package one may switch between those two sets of EOM with the keywords `h-proj`, and `proj-h` with obvious meaning.

It is illustrative to study the separable case $H = \sum_{\kappa} h^{(\kappa)}$, *i.e.* $H_R \equiv 0$.

$\hat{g}^{(\kappa)} \equiv 0$:

$$\boxed{\begin{aligned} i\dot{A}_J &= \sum_L \sum_{\kappa} \langle \Phi_J | h^{(\kappa)} | \Phi_L \rangle A_L = \sum_{\kappa=1}^f \sum_{l=1}^{n_{\kappa}} \langle \varphi_{j\kappa}^{(\kappa)} | h^{(\kappa)} | \varphi_{l\kappa}^{(\kappa)} \rangle A_{J_l^{\kappa}} \\ i\dot{\varphi}_j^{(\kappa)} &= (1 - P^{(\kappa)}) h^{(\kappa)} \varphi_j^{(\kappa)} \end{aligned}} \quad (3.58)$$

$\hat{g}^{(\kappa)} = h^{(\kappa)}$:

$$\boxed{\begin{aligned} i\dot{A}_J &= 0 \\ i\dot{\varphi}_j^{(\kappa)} &= h^{(\kappa)} \varphi_j^{(\kappa)} \end{aligned}} \quad (3.59)$$

This suggests that the choice $\hat{g}^{(\kappa)} = h^{(\kappa)}$ is of advantage, at least if H_R is small compared to the separable part $\sum h^{(\kappa)}$. However, the constant mean-field (CMF) integration scheme, which will be discussed later, is more useful with the constraint $\hat{g}^{(\kappa)} = 0$.

3.4 MCTDH-EOM for $\hat{g}^{(\kappa)} \neq 0$

We want to re-derive the EOM but this time for the general case $\hat{g}^{(\kappa)} \neq 0$. For part 1 of the Eq. (3.29) we obtain (see also (3.34)):

$$\begin{aligned} i \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle \dot{A}_L &= \\ \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle \langle \Phi_L | H | \Psi \rangle - \sum_{\nu=1}^f \sum_{k=1}^{n_{\nu}} \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle g_{l_{\nu}k}^{(\nu)} A_{L_k^{\nu}} &= \\ P^{(\kappa)} \langle \Psi_j^{(\kappa)} | H | \Psi \rangle - \sum_{l_{\kappa}, k} \rho_{jk}^{(\kappa)} g_{l_{\kappa}k}^{(\kappa)} \varphi_{l_{\kappa}}^{(\kappa)} - D & \end{aligned} \quad (3.60)$$

where

$$D = \sum_{\nu \neq \kappa} \sum_L \sum_k \langle \Psi_j^{(\kappa)} | \Phi_L \rangle g_{l_{\nu}k}^{(\nu)} A_{L_k^{\nu}} \quad (3.61)$$

The term $\nu = \kappa$ yields

$$\begin{aligned} \sum_k \sum_{L^{\kappa}} \sum_{l_{\kappa}} \langle \Psi_j^{(\kappa)} | \Phi_{L^{\kappa}} \varphi_{l_{\kappa}}^{(\kappa)} \rangle g_{l_{\kappa}k}^{(\kappa)} A_{L_k^{\kappa}} &= \\ \sum_{kl_{\kappa}} \langle \Psi_j^{(\kappa)} | \Psi_k^{(\kappa)} \rangle \varphi_{l_{\kappa}}^{(\kappa)} g_{l_{\kappa}k}^{(\kappa)} = \sum_{kl_{\kappa}} \rho_{jk}^{(\kappa)} g_{l_{\kappa}k}^{(\kappa)} \varphi_{l_{\kappa}}^{(\kappa)} & \end{aligned} \quad (3.62)$$

which proves Eq. (3.60). Part 2 of Eq. (3.29) now reads

$$i \langle \Psi_j^{(\kappa)} | \sum_{\nu=1}^f \sum_{l=1}^{n_{\nu}} \dot{\varphi}_l^{(\nu)} \Psi_l^{(\nu)} \rangle = i \sum_l \rho_{jl}^{(\kappa)} \dot{\varphi}_l^{(\kappa)} + D' \quad (3.63)$$

where

$$D' = \sum_{\nu \neq \kappa} \sum_l \langle \Psi_j^{(\kappa)} | \dot{\varphi}_l^{(\nu)} \Psi_l^{(\nu)} \rangle g_{l_{\nu}k}^{(\nu)} A_{L_k^{\nu}} \quad (3.64)$$

We will show later that $D = D'$. Hence adding part 1, Eq. (3.60), and part 2, Eq. (3.63), Eq. (3.29) turns into

$$\begin{aligned} \sum_l \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} &= \\ P^{(\kappa)} \sum_l \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} - \sum_{l,\kappa,k} \rho_{jk}^{(\kappa)} g_{l,\kappa k}^{(\kappa)} \varphi_{l,\kappa}^{(\kappa)} - D + i \sum_l \rho_{jl}^{(\kappa)} \dot{\varphi}_l^{(\kappa)} + D' \end{aligned}$$

or, assuming $D = D'$

$$i \sum_l \rho_{jl}^{(\kappa)} \dot{\varphi}_l^{(\kappa)} = (1 - P^{(\kappa)}) \sum_l \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} + \sum_{l,\kappa,k} \rho_{jk}^{(\kappa)} g_{l,\kappa k}^{(\kappa)} \varphi_{l,\kappa}^{(\kappa)} \quad (3.65)$$

Writing

$$\boldsymbol{\varphi}^{(\kappa)} = (\varphi_1^{(\kappa)} \dots \varphi_{n_\kappa}^{(\kappa)})^T \quad (3.66)$$

and multiplying by $\boldsymbol{\rho}^{-1}$ yields

$$\boxed{i \dot{\boldsymbol{\varphi}}^{(\kappa)} = (\mathbf{g}^{(\kappa)T} + (1 - P^{(\kappa)}) \boldsymbol{\rho}^{(\kappa)-1} \langle \mathbf{H} \rangle^{(\kappa)}) \boldsymbol{\varphi}^{(\kappa)}} \quad (3.67)$$

As

$$(\mathbf{g}^{(\kappa)T} \boldsymbol{\varphi}^{(\kappa)})_j = \sum_l |\varphi_l\rangle \langle \varphi_l | \hat{g}^{(\kappa)} | \varphi_j \rangle = P^{(\kappa)} g^{(\kappa)} \varphi_j^{(\kappa)} \quad (3.68)$$

Hence we also have

$$\boxed{i \dot{\boldsymbol{\varphi}}^{(\kappa)} = (P^{(\kappa)} \mathbf{g}^{(\kappa)} + (1 - P^{(\kappa)}) \boldsymbol{\rho}^{(\kappa)-1} \langle \mathbf{H} \rangle^{(\kappa)}) \boldsymbol{\varphi}^{(\kappa)}} \quad (3.69)$$

and from this all other forms follow.

Finally, we use again the separation

$$H = \sum_{\kappa} g^{(\kappa)} + H_R$$

yielding

$$\langle \Phi_J | H | \Phi_L \rangle = \langle \Phi_J | H_R | \Phi_L \rangle + \sum_{\kappa} \sum_{l,\kappa} g_{j,\kappa l,\kappa}^{(\kappa)} \delta_{J^{\kappa} L^{\kappa}} \quad (3.70)$$

and

$$i \dot{A}_J = \sum_L \langle \Phi_J | H_R | \Phi_L \rangle A_L + \sum_{\kappa} \sum_{l,\kappa} g_{j,\kappa l,\kappa}^{(\kappa)} A_{J_{l,\kappa}^{\kappa}} - \sum_{\kappa} \sum_l g_{j,\kappa l,\kappa}^{(\kappa)} A_{J_l^{\kappa}} \quad (3.71)$$

Hence

$$\begin{aligned} i \dot{A}_J &= \sum_L \langle \Phi_J | H_R | \Phi_L \rangle A_L + \sum_{\kappa} \sum_l g_{j,\kappa l,\kappa}^{(\kappa)} A_{J_{l,\kappa}^{\kappa}} \\ &= \sum_L \langle \Phi_J | H - \sum_{\kappa} \hat{g}^{(\kappa)} | \Phi_L \rangle A_L \end{aligned} \quad (3.72)$$

We still have to show that $D = D'$.

$$D = \sum_{\nu \neq \kappa} \sum_L \sum_k \langle \Psi_j^{(\kappa)} | \Phi_L \rangle g_{l,\kappa k}^{(\nu)} A_{L_k^\nu}$$

$$D' = i \sum_{\nu \neq \kappa} \sum_l \langle \Psi_j^{(\kappa)} | \dot{\varphi}_l^{(\nu)} \Psi_l^{(\nu)} \rangle$$

We insert $P^{(\nu)}$ in the equation for D' and, given that $\langle \Psi_j^{(\kappa)} | P^{(\nu)} = \langle \Psi_j^{(\kappa)} |$ for $\nu \neq \kappa$, we obtain

$$\begin{aligned} D' &= i \sum_{\nu \neq \kappa} \sum_l \langle \Psi_j^{(\kappa)} | \sum_{l_\nu} |\varphi_{l_\nu}^{(\nu)} \rangle \langle \varphi_{l_\nu}^{(\nu)} | \dot{\varphi}_l^{(\nu)} \rangle \Psi_l^{(\nu)} \rangle \\ &= \sum_{\nu \neq \kappa} \sum_l \sum_{l_\nu} g_{l_\nu l}^{(\nu)} \langle \Psi_j^{(\kappa)} | \varphi_{l_\nu}^{(\nu)} \sum_{L^\nu} A_{L_l^\nu} \Phi_{L^\nu} \rangle \\ &= \sum_{\nu \neq \kappa} \sum_l \sum_L \langle \Psi_j^{(\kappa)} | \Phi_L \rangle g_{l_\nu l}^{(\nu)} A_{L_l^\nu} = D \end{aligned} \quad (3.73)$$

In summary, we again display the EOM in various forms

$$\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L - \sum_{\kappa=1}^f \sum_{l=1}^{n_\kappa} g_{j\kappa l}^{(\kappa)} A_{J_l^\kappa} \\ &= \sum_L \langle \Phi_J | H - \sum_{\kappa=1} g^{(\kappa)} | \Phi_L \rangle A_L \end{aligned} \quad (3.74)$$

$$\begin{aligned} i\dot{\varphi}^{(\kappa)} &= \{g^{(\kappa)} \mathbf{1} + (1 - P^{(\kappa)}) [\rho^{(\kappa)-1} \langle \mathbf{H} \rangle^{(\kappa)} - g^{(\kappa)} \mathbf{1}]\} \varphi^{(\kappa)} \\ &= P^{(\kappa)} \hat{g} \varphi^{(\kappa)} + (1 - P^{(\kappa)}) \rho^{(\kappa)-1} \langle \mathbf{H} \rangle^{(\kappa)} \varphi^{(\kappa)} \\ &= [(g^{(\kappa)})^T + (1 - P^{(\kappa)}) \rho^{(\kappa)-1} \langle \mathbf{H} \rangle^{(\kappa)}] \varphi^{(\kappa)} \\ &= \{g^{(\kappa)} \mathbf{1}\}^T + (1 - P^{(\kappa)}) \rho^{(\kappa)-1} \langle \mathbf{H} - \sum g^{(\kappa)} \rangle^{(\kappa)} \} \varphi^{(\kappa)} \end{aligned} \quad (3.75)$$

For the separation

$$H = \sum_{\kappa} h^{(\kappa)} + H_R \quad (3.76)$$

one obtains for $\hat{g}^{(\kappa)} \equiv 0$

$$\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H | \Phi_L \rangle A_L \\ i\dot{\varphi}^{(\kappa)} &= (1 - P^{(\kappa)}) (h^{(\kappa)} \mathbf{1} + \rho^{(\kappa)-1} \langle \mathbf{H}_R \rangle) \varphi^{(\kappa)} \end{aligned} \quad (3.77)$$

and for $g^{(\kappa)} = h^{(\kappa)}$

$$\begin{aligned} i\dot{A}_J &= \sum_L \langle \Phi_J | H_R | \Phi_L \rangle A_L \\ i\dot{\varphi}^{(\kappa)} &= (h^{(\kappa)} \mathbf{1} + (1 - P^{(\kappa)}) \rho^{(\kappa)-1} \langle \mathbf{H}_R \rangle) \varphi^{(\kappa)} \end{aligned} \quad (3.78)$$

There are two sets of EOMs which are used in the Heidelberg MCTDH code.

3.5 Memory consumption

If the Hamiltonian is well structured, the memory demand to store it can be neglected. In the standard method one needs (at least) to keep 3 WF-vectors in RAM to perform propagation, setting $N_\kappa = N$ for all κ one hence needs

$$3 \times N^f \times \text{complex16} \quad \text{bytes}$$

The MCTDH method, on the other hand, requires n^f numbers to represent the A -vector and $f \cdot n \cdot N$ numbers to represent the SPFs. Hence the storage demand is

$$12 \times (n^f + f \cdot n \cdot N) \times \text{complex16} \quad (3.79)$$

where the factor 12 accounts for the fact that one approximately needs an equivalent of about 12 WF to store all the work-arrays, mean-fields, etc.

Let us consider an example with $N = 32$ grid points and $n = 7$ SPFs for each degree of freedom.

f	St. Method	MCTDH	n^f	$f \cdot n \cdot N$
3	1.54 MB	190 KB	343	672
4	48 MB	620 KB	2401	896
6	48 GB	22 MB	$117 \cdot 10^3$	1344
9	1.54 PB	7.2 GB	$40 \cdot 10^6$	2016

Hence MCTDH shows a big advantage over the standard method. We can go to $9D$ and for small n 's, *e.g.* $n = 4$, even to $12D$. However, we are still plagued by exponential scaling, n^f , although it is much smaller than the N^f scaling of the standard method, here 7^f versus 32^f .

The numerical effort is more difficult to estimate as it depends on integration step size etc. However, for one step the effort of the standard method is

$$\text{effort}_{\text{St.Method}} \approx c_0 \cdot f \cdot N^{f+1} \quad (3.80)$$

and for MCTDH

$$\text{effort}_{\text{MCTDH}} \approx c_1 \cdot s \cdot f \cdot n \cdot N^2 + c_2 \cdot s \cdot f^2 \cdot n^{f+1} \quad (3.81)$$

where c_0 , c_1 and c_2 are constants of proportionality. s denotes the number of Hamiltonian terms.

If the Hamiltonian would be a full $N_{tot} \times N_{tot}$ matrix with $N_{tot} = N^f$ then the (matrix \times vector) operation $H\Psi$ would take, of course, N^{2f} operations. However, we are using DVR's and for the standard method $V\Psi$ takes only N^f operations. The kinetic energy operator tensorizes, *i.e.* is of product form

$$T = \sum_{r=1}^{s'} T^{(r)} = \sum_{r=1}^{s'} T^{(1,r)} \dots T^{(f,r)} \quad (3.82)$$

with only few terms ($s' \approx f$) and several of the $T^{(\kappa,r)}$ will be unit operators. Note that $T^{(\kappa,r)}$ operates on the κ -th degree of freedom only

$$(T^{(r)}\Psi)_{i_1,\dots,i_f} = \sum_{j_1,\dots,j_f} T_{i_1 j_1}^{(1,r)} T_{i_2 j_2}^{(2,r)} \dots T_{i_f j_f}^{(f,r)} \Psi_{j_1,\dots,j_f} \quad (3.83)$$

(Note that here we use Ψ_{j_1,\dots,j_f} for the C -vector C_{j_1,\dots,j_f} of the standard method, Eq. 2.7).

We can do the matrix multiplication successively:

Define:

$$\Psi_{i_1 \dots i_f}^{(0,r)} = \Psi_{i_1 \dots i_f}$$

For $\kappa = 1, \dots, f$ do:

$$\Psi_{i_1 \dots i_f}^{(\kappa,r)} = \sum_{j_\kappa} T_{i_\kappa j_\kappa}^{(\kappa,r)} \Psi_{i_1 \dots i_{\kappa-1} j_\kappa \dots i_f}^{(\kappa-1,r)} \quad (3.84)$$

Finally:

$$(T\Psi)_{i_1 \dots i_f} = \sum_{r=1}^{s'} \Psi_{i_1 \dots i_f}^{(f,r)}$$

The matrix multiplication (3.84) takes N^{f+1} operations. There are f iterations for each s , hence the total effort is

$$s' \cdot f \cdot N^{f+1} \quad (3.85)$$

This trick is used over and over again in MCTDH. It is important to understand it clearly. It is a very powerful method as it reduces the effort from N^{2f} (or n^{2f}) to $f \cdot N^{f+1}$ (or $f \cdot n^{f+1}$), however, it requires a product form of the Hamiltonian. Since s' is usually small and since several of the $T^{(\kappa,r)}$ are unit operators (which do not require a matrix multiplication) we estimate the effort simply as

$$\text{effort}_{\text{St.Method}} = c_0 \cdot f \cdot N^{f+1} \quad (3.86)$$

For the MCTDH-effort the first term refers to the propagation of the SPFs (for potential terms N^2 is replaced by N) and the second part is the propagation of the A-vector and the build up of the mean-fields (there are f mean-fields, turning f into f^2).

$$\text{effort}_{\text{MCTDH}} = c_1 \cdot s \cdot f \cdot n \cdot N^2 + c_2 \cdot s \cdot f^2 \cdot n^{f+1} \quad (3.87)$$

For large systems the second part will dominate, both for memory and effort. This allows us to estimate the gain for large systems compactly as

$$\text{gain}_{\text{mem}} = \frac{1}{4} \left(\frac{N}{n}\right)^f \quad (3.88)$$

$$\text{gain}_{\text{CPU}} = \frac{c_0}{c_2} \frac{1}{sf} \left(\frac{N}{n}\right)^{f+1} \quad (3.89)$$

The important factor is in both cases the contraction N/n .³ The limiting factor of large MCTDH calculations, for both memory and effort, is the A-vector length n^f . The A-vector length can be reduced by a trick called *mode-combination*. Mode-combination allows us to tackle systems with more than $12D$ with MCTDH.

3.6 Mode combination

The single-particle functions do not need to depend on one coordinate alone, they may depend on several coordinates. We group together several physical coordinates into one logical coordinate, also called *particle* or *combined mode*

$$Q_\kappa \equiv (q_{\kappa,1}, q_{\kappa,2}, \dots, q_{\kappa,d}) \quad (3.90)$$

$$\varphi_j^{(\kappa)}(Q_\kappa, t) = \varphi_j^{(\kappa)}(q_{\kappa,1}, q_{\kappa,2}, \dots, q_{\kappa,d}, t) \quad (3.91)$$

The MCTDH wavefunction is now expanded as

$$\Psi(q_1, \dots, q_f, t) \equiv \Psi(Q_1, \dots, Q_p, t) = \sum_{j_1 \dots j_p} A_{j_1 \dots j_p}(t) \prod_{\kappa=1}^p \varphi_{j_\kappa}^{(\kappa)}(Q_\kappa, t) \quad (3.92)$$

and the SPFs themselves are expanded as:

$$\varphi_j^{(\kappa)}(Q_\kappa, t) = \sum_{i_1 \dots i_d} C_{i_1 \dots i_d}^{(\kappa, j)}(t) \chi^{(\kappa,1)}(q_{\kappa,1}) \dots \chi^{(\kappa,d)}(q_{\kappa,d}) \quad (3.93)$$

Moreover, the number of SPFs per particle needed for convergence will increase with mode combination. If $\tilde{n} = n^d$ would hold, there would be no gain, the A-vector length would not change. Luckily one finds as a rule of thumb:⁴

$$\tilde{n} \approx d \cdot n \quad (3.94)$$

sometimes even less. Note that now all correlation between the DOFs within a particle is taken care of at the SPF level. Only the correlation between particles has to be accomplished by the A-vector.

The MCTDH memory requirement and effort using mode-combination reads of course

$$\begin{aligned} \text{mem} &\approx 12 \times (\tilde{n}^p + p \cdot \tilde{n} \cdot N^d) \times \text{complex16} \\ \text{effort} &\approx c_1 \cdot s \cdot p \cdot d \cdot \tilde{n} \cdot N^{d+1} + c_2 \cdot s \cdot p^2 \cdot \tilde{n}^{p+1} \end{aligned}$$

³More general:

$$\begin{aligned} N^f &\rightarrow \prod_{\kappa=1}^f N_\kappa \\ N^{f+1} &\rightarrow \left(\frac{1}{f} \sum_{\kappa=1}^f N_\kappa\right) \cdot \prod_{\kappa=1}^f N_\kappa \end{aligned}$$

and similar for n^f and n^{f+1} .

⁴ \tilde{n} denotes the number of SPFs needed for convergence when mode-combination is used. n is the corresponding number of SPFs without mode-combination. For the sake of simplicity it is assumed that $n_\kappa = n$ for all κ , and similarly for \tilde{n} , N , and \tilde{N} .

and in the gain formulas Eq. (3.88-3.89) N , n , and f are to be replaced by \tilde{N} , \tilde{n} , and p , respectively.

The great success of mode-combination is demonstrated by the following table, where we assume

$$N = 32 \quad \tilde{N} = 1024 \quad \text{or} \quad 32768 \quad (d = 1, 2, 3)$$

grid points for uncombined and doubly or triply combined grids, respectively. Similarly, we assume

$$n = 7 \quad \tilde{n} = 15 \quad \text{or} \quad 23$$

as numbers of SPFs. In realistic cases there are in general several DOFs which

Table 3.1: Comparison of memory consumption of the standard method and MCTDH with and without mode-combination $N = 32$, $\tilde{N} = 1024$ or 32768 and $n = 7$, $\tilde{n} = 15$ or 23 are assumed. The best value for each row is shown in bold face.

f	St. Method	MDTCH	2-mode	3-mode
2	48 kB	282 kB	-	-
4	48 MB	620 kB	6 MB	-
6	48 GB	22 MB	10 MB	290 MB
8	48 TB	1.03 GB	22 MB	290 MB
10	48 PB	51 GB	160 MB	310 MB
12	-	2.4 TB	2.2 GB	620 MB
15	-	-	210 GB	1.9 GB
18	-	-	7.38 TB	29.3 GB

do not couple strongly and may be represented by few grid-points (5-10, say) only. Such DOFs can be combined to a high degree ($d=4$ or 5 , say), making it possible to treat systems with more than 30 DOFs.

The usefulness of mode-combination is limited by the fact that multi-dimensional SPFs have to be propagated. If one "over combines", the propagation of the SPFs will take more effort than the propagation of the A-vector and efficiency is lost. However, we know a method which efficiently propagates multi-dimensional wavefunctions: MCTDH!

One hence may think of propagating the SPFs of an MCTDH calculation by MCTDH. This idea has led to the development of a multi-layer MCTDH (ML-MCTDH) algorithm.

Chapter 4

The constant mean-field (CMF) integration scheme

The MCTDH equations of motion (for $\hat{g} \equiv 0$ and $H = \sum_{\kappa} h^{(\kappa)} + H_R$) read

$$i\dot{A}_J = \sum_L \mathcal{K}_{JL} A_L \quad (4.1)$$

$$i\dot{\varphi}_j^{(\kappa)} = (1 - P^{(\kappa)}) \{ h^{(\kappa)} \varphi_j^{(\kappa)} + \sum_{k,l=1}^{n_{\kappa}} (\rho^{(\kappa)})_{jk}^{-1} \mathcal{H}_{lk}^{(\kappa)} \varphi_l^{(\kappa)} \} \quad (4.2)$$

with

$$\mathcal{K}_{JL} = \langle \Phi_J | H | \Phi_L \rangle \quad \text{and} \quad \mathcal{H}_{lk}^{(\kappa)} = \langle H_R \rangle_{lk}^{(\kappa)}$$

This set of non-linear coupled differential equations can be solved by a standard all-purpose integrator (Runge-Kutta, Adams-Bashforth-Moulton). The problem is that the mean-fields $\mathcal{H}_{lk}^{(\kappa)}$ and the \mathcal{K} -matrix \mathcal{K}_{JL} have to be built at every time step. The time-steps, however, have to be small as one has to describe an oscillating function.

Formally Ψ is given by

$$\Psi(t) = \sum_n a_n \Psi_n e^{-iE_n t}, \quad H\Psi_n = E_n \Psi_n \quad (4.3)$$

To integrate $e^{-iE_n t}$ one needs step-sizes of the order

$$\Delta t \lesssim \frac{1}{|E_n|} \quad (4.4)$$

Hence the step-size is determined by the absolute largest eigenvalue of the matrix representation of the Hamiltonian.

The mean-fields, on the other hand, are not that strongly oscillating. It is hence tempting to set the mean-fields constant over a larger update time-step τ and to integrate the A-vector and the SPFs with much smaller time-steps.

Keeping the mean-fields constant yields

$$i\dot{A}_J = \sum_L \bar{\mathcal{K}}_{JL} A_L \quad (4.5)$$

$$i\dot{\varphi}_j^{(1)} = (1 - P^{(1)}) \{ h^{(1)} \varphi_j^{(1)} + \sum \bar{\rho}_{jk}^{(1)-1} \bar{\mathcal{H}}_{lk}^{(1)} \varphi_l^{(1)} \} \quad (4.6)$$

$$\vdots$$

$$i\dot{\varphi}_j^{(f)} = (1 - P^{(f)}) \{ h^{(f)} \varphi_j^{(f)} + \sum \bar{\rho}_{jk}^{(f)-1} \bar{\mathcal{H}}_{lk}^{(f)} \varphi_l^{(f)} \} \quad (4.7)$$

Note that all the differential equations *decouple!* The bar indicates that the quantities are kept constant over the update time-step τ . As the equations decouple, one can use different time-steps and in fact different integrators for each set of equations. The EOM for the A-vector is now *linear* and one may use an adapted integrator like Short Iterative Lanczos (SIL). The EOM for the SPFs are still non-linear because of the projector $P^{(\kappa)}$. But the main gain is of course that the mean fields need to be build less often.

The scheme outlined above is too simple. One needs at least a second order scheme, *i.e.* one in which the error scales like $\|\Psi_{ex} - \Psi\| \sim \tau^2$. In the present scheme, the error scales like τ .

A higher-order scheme looks like:

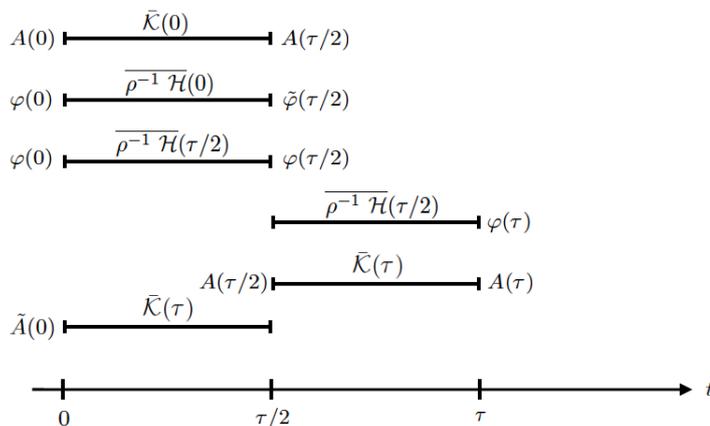


Figure 4.1: Second order CMF scheme.

in lowest order

$$\|\Psi - \tilde{\Psi}\| = \|\Delta A\|^2 + \sum_{\kappa=1}^f \text{tr}(\Delta O \cdot \rho^{(\kappa)}) \quad (4.8)$$

where

$$\Delta A = A - \tilde{A} \quad (4.9)$$

$$\Delta O_{jl} = \langle \Delta \varphi_j | \varphi_l \rangle \quad (4.10)$$

$$\Delta \varphi_j = \varphi_j - \tilde{\varphi}_j \quad (4.11)$$

This allows for an automatic step-size control. One sets an error limit and the algorithm searches for an appropriate value of τ .

To demonstrate that the scheme Fig. 4.1 gives an improved scaling of the error, let us consider a one-dimensional differential equation. The Taylor expansion of the solution propagated by one step reads:

$$y(\tau) = y(0) + y'(0) \cdot \tau + \frac{1}{2} y''(0) \cdot \tau^2 + \frac{1}{6} y'''(0) \cdot \tau^3 + \dots \quad (4.12)$$

The previous scheme, Eqs.(4.5-4.7), is equivalent to an Euler integrator

$$y^{\text{app}}(\tau) = y(0) + y'(0) \cdot \tau \quad (4.13)$$

which has an error

$$\text{error} : (y^{\text{app}} - y)(\tau) = -\frac{1}{2} y''(0) \cdot \tau^2 + \dots \quad (4.14)$$

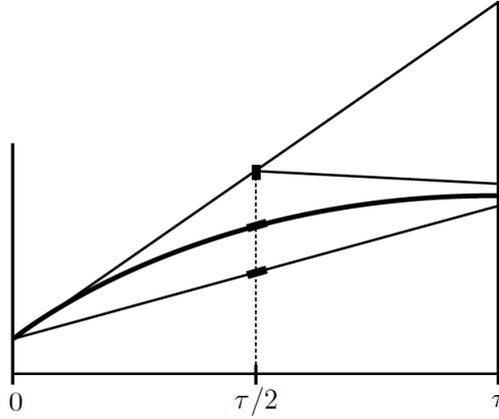


Figure 4.2: Graphical interpretation of the numerical integration. The heavy line (middle) shows an exact solution of a differential equation. Taking the initial derivative $y'(0)$ throughout the propagation leads to a rather large error at $t = \tau$. See upper straight line. Using $y'(\tau/2)$ rather than $y'(0)$ provides a much better solution. See the lowest straight line. And using $y'(0)$ for the first half-step and $y'(\tau)$ for the second half-step also provides a good approximate solution.

To investigate this error introduced by the scheme Fig. 4.1 for the SPFs, we first note that the time-derivative at a half step reads

$$y'(\tau/2) = y'(0) + y''(0) \cdot \tau/2 + \frac{1}{2} y'''(0) \cdot (\tau/2)^2 \quad (4.15)$$

The one-step propagated solution, using this mid-step derivative, reads

$$y^{\text{app}}(\tau) = y(0) + y'(\tau/2) \cdot \tau = y(0) + y'(0) \cdot \tau + y''(0) \cdot \tau^2/2 + y'''(0) \cdot \tau^3/8 \quad (4.16)$$

and has the error

$$\text{error} : (y^{\text{app}} - y)(\tau) = \left(\frac{1}{8} - \frac{1}{6}\right) y'''(0) \cdot \tau^3 = -\frac{1}{24} y'''(0) \cdot \tau^3 \quad (4.17)$$

Similarly for the propagator of the A-vector, we obtain

$$\begin{aligned} y^{\text{app}}(\tau) &= y(0) + y'(0) \cdot (\tau/2) + y'(\tau) \cdot (\tau/2) \\ &= y(0) + y'(0) \cdot \tau + y''(0) \cdot (\tau^2/2) + \frac{1}{4} y'''(0) \cdot \tau^3 \end{aligned} \quad (4.18)$$

and the error

$$\text{error} : \left(\frac{1}{4} - \frac{1}{6}\right) y'''(0) \cdot \tau^3 = \frac{1}{12} y'''(0) \cdot \tau^3 \quad (4.19)$$

Hence the error done in one step scales like τ^3 . The total error then scales like τ^2 as the number of steps scales like τ^{-1} .

To understand why CMF works, let us consider a separable case

$$H = \sum_{\kappa=1}^f h^{(\kappa)} \quad (4.20)$$

hence

$$\rho^{(\kappa)-1} \mathcal{H}^{(\kappa)} = h^{(\kappa)} \mathbf{1} + \epsilon \quad (4.21)$$

The matrix ϵ is irrelevant because of the projector

$$\mathcal{K}_{JL} = \langle \Phi_J | \hat{H} | \Phi_L \rangle = \sum_{\kappa=1}^f \langle \varphi_{j\kappa}^{(\kappa)} | h^{(\kappa)} | \varphi_{l\kappa}^{(\kappa)} \rangle \delta_{J\kappa L\kappa} \quad (4.22)$$

The mean-fields, $\rho^{-1} \mathcal{H}$, are obviously constant, but what is with \mathcal{K}_{JL} ?
The EOMs for the φ 's read (drop κ):

$$i\dot{\varphi}_j = g \varphi_j + (1 - P) \cdot (h - g) \varphi_j \quad (4.23)$$

From this follows:

$$\begin{aligned} \frac{d}{dt} \langle \varphi_j | h | \varphi_l \rangle &= \\ &-i \langle g \varphi_j + (1 - P)(h - g) | h | \varphi_l \rangle + i \langle \varphi_j | h | g \varphi_l + (1 - P)(h - g) \varphi_l \rangle \\ &= i \langle \varphi_j | g^\dagger h + (h^\dagger - g^\dagger)(1 - P)h - hg + h(1 - P)(h - g) | \varphi_l \rangle \\ &\stackrel{\{g^\dagger = g\}}{=} i \langle \varphi_j | (h^\dagger - h)(1 - P)h | \varphi_l \rangle + i \langle \varphi_j | gPh - hPg | \varphi_l \rangle \end{aligned} \quad (4.24)$$

hence

$$\frac{d}{dt} \mathcal{K}_{JL} = 0 \quad \text{if } h^{(\kappa)} = h^{(\kappa)\dagger} \quad (4.25)$$

$$\text{and } [P^{(\kappa)} h^{(\kappa)} P^{(\kappa)}, P^{(\kappa)} g^{(\kappa)} P^{(\kappa)}] = 0 \quad (4.26)$$

i.e. if the projected h and the projected constraint commute. This is true for $g \equiv 0$ and $g^{(\kappa)} = h^{(\kappa)}$, the standard choices!

Hence the CMF integrator can take arbitrarily large update steps τ if the Hamiltonian is separable. In a scattering problem, the Hamiltonian often becomes almost separable when the colliding partners are far from each other. However, when the scattered particle is finally absorbed by a Complex Absorbing Potential (CAP) the separable Hamiltonian becomes non-hermitian and the CMF-integrator is forced to take small steps. But our analysis has clearly shown, that the assumption of constant mean-fields is violated by the non-separable (and non-hermitian) terms of the Hamiltonian. These terms are usually much smaller than the separable ones, which justifies the assumption that the mean-fields can be taken as constant over a small update time τ , which, however, is much larger than the integration steps used to propagate the SPFs.

The CMF integrator scheme violates energy conservation which should hold for constant hermitian Hamiltonians. Only for $\tau \rightarrow 0$ energy conservation is strictly obeyed. If an MCTDH calculation shows an energy deviation which is too high to be acceptable, one must increase the integrator accuracies, in particular the CMF accuracy.

Chapter 5

Relaxation and improved relaxation

A ground state wavefunction can be obtained by a time-dependent method via relaxation, *i.e.* propagation in negative imaginary time. The Schrödinger equation is then turned into

$$\dot{\Psi} = -H \Psi \quad (5.1)$$

To see the effect we expand the WF in eigenstates and obtain

$$\Psi(t) = \sum_n a_n e^{-E_n t} \Psi_n \quad (5.2)$$

The state with the lowest energy (usually E_0) will "win". Of course the norm must be restored. To avoid this, one may change the Schrödinger equation to

$$\dot{\Psi}(t) = -(H - E(t)) \Psi(t) \quad \text{where} \quad E(t) = \langle \Psi(t) | H | \Psi(t) \rangle \quad (5.3)$$

Then

$$\langle \Psi(t) | \dot{\Psi}(t) \rangle = 0 \quad \Rightarrow \quad \frac{d}{dt} \|\Psi\|^2 = 0 \quad (5.4)$$

The energy E can be interpreted as a Lagrange parameter introduced to keep the norm of Ψ constant (we assume Ψ to be normalized). Differentiation of $E(t)$ leads to

$$\dot{E} = -\langle \Psi(t) | (H - E(t))^2 | \Psi(t) \rangle. \quad (5.5)$$

Hence the energy decreases with relaxation time and converges if the variance vanishes, *i.e.* if the wave function becomes an eigenstate of H . Usually this will be the ground state, only if the initial state is orthogonal to the ground state the algorithm may converge to an excited state.

Relaxation works well if the initial state Ψ has a reasonable overlap with the ground state and if the ground state is well separated. However relaxation may converge slowly if the energy of the first excited state, E_1 , is close to the ground state energy E_0 . To damp out the contribution of the excited state one needs a propagation time which satisfies $(E_1 - E_0) \cdot t \approx 10 - 30$.¹ The relaxation

¹Note 1 $eV \cdot 1 fs = 1.519\hbar$

can be accelerated and excited states can be computed as well, if the MCTDH A-vector is not determined by relaxation but by diagonalization. This method is called *improved relaxation*.

The algorithm can be derived via a standard time-independent variational principle $\delta\{\langle\Psi|H|\Psi\rangle - \text{constraints}\} = 0$

$$\delta\left\{\langle\Psi|H|\Psi\rangle - E\left(\sum_J A_J^* A_J - 1\right) - \sum_{\kappa=1}^f \sum_{j,l=1}^{n_\kappa} \epsilon_{jl}^{(\kappa)} (\langle\varphi_j^{(\kappa)}|\varphi_l^{(\kappa)}\rangle - \delta_{jl})\right\} = 0 \quad (5.6)$$

The first Lagrange parameter, E , ensures that the A-vector is normalized and the $\epsilon_{jl}^{(\kappa)}$ ensures that the SPFs are orthonormal. We note that

$$\langle\Psi|H|\Psi\rangle = \sum_{JK} A_J^* H_{JK} A_K \quad H_{JK} = \langle\Phi_J|H|\Phi_K\rangle \quad (5.7)$$

Varying A_J^* yields

$$\sum_K H_{JK} A_K = E A_J \quad (5.8)$$

Hence the coefficient vector is obtained as an eigenvector of the Hamiltonian matrix represented in the basis of the SPFs. Using

$$\langle\Psi|H|\Psi\rangle = \left\langle \sum_j \Psi_j^{(\kappa)} \varphi_j^{(\kappa)} \middle| H \middle| \sum_l \Psi_l^{(\kappa)} \varphi_l^{(\kappa)} \right\rangle = \sum_{j,l} \varphi_j^{(\kappa)*} \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} \quad (5.9)$$

and varying with respect to $\Psi_j^{(\kappa)*}$ yields

$$\sum_{l=1}^{n_\kappa} \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} = \sum_{l=1}^{n_\kappa} \epsilon_{jl}^{(\kappa)} \varphi_l^{(\kappa)} \quad (5.10)$$

Projecting this equation onto $\varphi_k^{(\kappa)}$ yields

$$\epsilon_{jl}^{(\kappa)} = \sum_l \langle \varphi_k^{(\kappa)} | \langle H \rangle_{jl}^{(\kappa)} | \varphi_l^{(\kappa)} \rangle \quad (5.11)$$

and from that follows

$$(1 - P^{(\kappa)}) \sum_{l=1}^{n_\kappa} \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} = 0 \quad (5.12)$$

As this equation holds for any j , it must hold for any linear combination as well. To arrive at a form similar to the MCTDH equations of motion we insert the inverse of the density operator

$$\dot{\varphi}_j^{(\kappa)} := -(1 - P^{(\kappa)}) \sum_{\kappa,l} (\rho^{(\kappa)})^{-1}_{jk} \langle H \rangle_{kl}^{(\kappa)} \varphi_l^{(\kappa)} = 0 \quad (5.13)$$

with

$$\dot{\varphi} = \frac{\partial \varphi}{\partial \tau}, \quad \tau = -i t \quad (5.14)$$

This suggests that one can obtain the updated SPFs simply by relaxation. In fact, one can show that the energy changes during SPF-relaxation as

$$\dot{E} = -2 \sum_{\kappa=1}^f \sum_{l=1}^{n_{\kappa}} \left\| \sum_{j=1}^{n_{\kappa}} (\rho^{(\kappa)1/2})_{lj} \dot{\varphi}_j^{(\kappa)} \right\|^2 \leq 0 \quad (5.15)$$

From this we have that the orbital relaxation will always minimize the energy. As the energy cannot go down indefinitely it follows $\|\dot{\varphi}\| \rightarrow 0$ for $\tau \rightarrow \infty$ and hence Eq. (5.13) will be satisfied for a sufficiently long relaxation.

Proof of Eq. (5.15): The A-vector is kept constant during SPF-relaxation. The time-derivative of the energy hence reads

$$\dot{E} = 2 \operatorname{Re} \langle \dot{\Psi} | H | \Psi \rangle \quad (5.16)$$

$$= 2 \operatorname{Re} \langle \sum_{\kappa} \sum_j \dot{\varphi}_j^{(\kappa)} \Psi_j^{(\kappa)} | H | \Psi \rangle \quad (5.17)$$

$$= 2 \operatorname{Re} \sum_{\kappa} \sum_{j,l} \langle \dot{\varphi}_j^{(\kappa)} \Psi_j^{(\kappa)} | \varphi_l^{(\kappa)} \Psi_l^{(\kappa)} \rangle \quad (5.18)$$

$$= 2 \operatorname{Re} \sum_{\kappa} \sum_{j,l} \langle \dot{\varphi}_j^{(\kappa)} | \langle H \rangle_{jl}^{(\kappa)} | \varphi_l^{(\kappa)} \rangle \quad (5.19)$$

$$= 2 \operatorname{Re} \sum_{\kappa} \sum_{j,l} \langle \dot{\varphi}_j^{(\kappa)} | (1 - P) \langle H \rangle_{jl}^{(\kappa)} | \varphi_l^{(\kappa)} \rangle \quad (5.20)$$

As

$$- \sum_k \rho_{jk}^{(\kappa)} \dot{\varphi}_k^{(\kappa)} = (1 - P) \sum_l \langle H \rangle_{jl}^{(\kappa)} \varphi_l^{(\kappa)} \quad (5.21)$$

we have

$$\dot{E} = -2 \operatorname{Re} \sum_{\kappa} \sum_{j,k} \langle \dot{\varphi}_j^{(\kappa)} | \dot{\varphi}_k^{(\kappa)} \rangle \rho_{jk}^{(\kappa)} \quad (5.22)$$

$$= -2 \operatorname{Re} \sum_{\kappa} \sum_{j,k,l} \langle (\rho^{(\kappa)1/2})_{lj} \dot{\varphi}_j^{(\kappa)} | (\rho^{(\kappa)1/2})_{lk} \dot{\varphi}_k^{(\kappa)} \rangle \quad (5.23)$$

$$= -2 \sum_{\kappa} \sum_l \left\| \sum_j \rho_{lj}^{(\kappa)1/2} \dot{\varphi}_j^{(\kappa)} \right\|^2 \quad (5.24)$$

q.e.d.

Improved relaxation proceeds as follows: At first an initial state has to be defined. This state should have a reasonable overlap with the sought state. Then the matrix representation of the Hamiltonian H_{JK} is built and diagonalized by a Davidson routine.² Then the mean-fields are built and the SPFs are relaxed. After that, H_{JK} is built in the space of the new SPFs and the whole process is iterated till convergence.

If the ground state is computed, the selection of the eigenvector of the Hamiltonian is simple: one takes the eigenvector of lowest energy. When excited states

²Actually H_{JK} is never built as a full matrix but applied term by term to the A-vector.

are to be computed, that eigenvector is taken which corresponds to the wavefunction which has the largest overlap with the initial state.

An MCTDH always works, whatever the number of SPFs. If there are too few configurations, the propagation will be less accurate but usually still describes the overall features rather well. This is in contrast to *improved relaxation* which fails to converge when the configuration space is too small. There is never a problem in computing the ground state, but converging to excited states becomes more difficult the higher the excitation energy or, more precisely, the higher the density of states.

The *improved relaxation* algorithm may be used in block form, *i.e.* one may start with a block of initial vectors which then converge collectively to a set of eigenstates. Formally the different wave functions are treated as electronic states of one 'super wavefunction'. As the single-set algorithm is used, there is one set of SPFs for all wave functions. The mean-fields are hence state-averaged mean-fields and the Davidson routine is replaced by a block-Davidson one. The block form of *improved relaxation* is more efficient than the single vector one when several eigenstates are to be computed. However, the block form requires considerably more memory.

Improved relaxation has been applied quite successfully to a number of problems. For 4-atoms systems (6D) it is in general possible to compute all eigenstates of interest. For a system as large as H_5O_2^+ (15D) it was, of course, only possible to converge few low lying states.

Chapter 6

Correlation DVR (CDVR)

6.1 TD-DVR

The correlation DVR method (CDVR) method is not implemented in the Heidelberg MCTDH package. However, as it plays a central role in the MCTDH code of Uwe Manthe, we discuss it briefly here.

The idea¹ is to use the SPFs to build a DVR. This time-dependent DVR has much less points (as $n < N$) but may still be good enough as the SPFs are optimal for representing the WF.

Hence one diagonalizes the matrix representation of the position operator

$$Q_{jl}^{(\kappa)} = \langle \varphi_j^{(\kappa)} | \hat{q}^{(\kappa)} | \varphi_l^{(\kappa)} \rangle \quad (6.1)$$

to obtain the eigenvalues $q_\alpha^{(\kappa)}$ ($\alpha = 1, \dots, n_\kappa$) and the eigenvectors which are used to transform the SPFs and the A-vector to position orbitals $\xi_j^{(\kappa)}$.

$$\langle \xi_j^{(\kappa)} | \hat{q}^{(\kappa)} | \xi_l^{(\kappa)} \rangle = q_i^{(\kappa)} \delta_{jl} \quad (6.2)$$

In this DVR, V_{JL} is given by

$$\begin{aligned} V_{JL} &= \langle \xi_{j_1}^{(1)} \dots \xi_{j_f}^{(f)} | V(q_1, \dots, q_f) | \xi_{l_1}^{(1)} \dots \xi_{l_f}^{(f)} \rangle \\ &= V(q_{j_1}^{(1)}, \dots, q_{j_f}^{(f)}) \cdot \delta_{j_1 l_1} \dots \delta_{j_f l_f} \end{aligned} \quad (6.3)$$

And similarly one proceeds to compute the mean-fields.

Hence one does an "ordinary" quadrature but not over the primitive grid which has N^f points but rather over a time-dependent adaptive grid of n^f points. This is an enormous reduction in effort and the n^f scaling law is similar to the MCTDH scaling laws. So it looks very promising. However, the error introduced is too large.

¹U. Manthe, H.-D. Meyer, L. S. Cederbaum, *J. Chem. Phys.* **97**, 3199, (1992).

6.2 CDVR

To improve the situation² we remark that the general MCTDH philosophy is to do the uncorrelated part correctly. Only for the correlated part one adopts an approximation (small numbers of SPFs).

To this end, one adds a correction term which ensures that one-dimensional potentials will be treated exactly, *i.e.* on the fine grid.

$$\begin{aligned}
 V_{JL} &= \langle \xi_{j_1}^{(1)} \cdots \xi_{j_f}^{(f)} | V(q_1 \cdots q_f) | \xi_{l_1}^{(1)} \cdots \xi_{l_f}^{(f)} \rangle \\
 &= V(q_{j_1}^{(1)} \cdots q_{j_f}^{(f)}) \cdot \delta_{j_1 l_1} \cdots \delta_{j_f l_f} \\
 &+ \sum_{\kappa=1}^f \langle \xi_{j_\kappa}^{(\kappa)} | \Delta V^{(\kappa)}(q_{j_1}^{(1)}, \dots, q_{\kappa-1}^{(\kappa-1)}, q_\kappa, q_{\kappa+1}^{(\kappa+1)}, \dots, q_{j_f}^{(f)}) | \xi_{l_\kappa}^{(\kappa)} \rangle \\
 &\times \delta_{j_1 l_1} \cdots \delta_{j_{\kappa-1} l_{\kappa-1}} \delta_{j_{\kappa+1} l_{\kappa+1}} \cdots \delta_{j_f l_f}
 \end{aligned} \tag{6.4}$$

where

$$\begin{aligned}
 \Delta V^{(\kappa)}(q_{j_1}^{(1)}, \dots, q_{\kappa-1}^{(\kappa-1)}, q_\kappa, q_{\kappa+1}^{(\kappa+1)}, \dots, q_{j_f}^{(f)}) = \\
 V(q_{j_1}^{(1)}, \dots, q_{\kappa-1}^{(\kappa-1)}, q_\kappa, q_{\kappa+1}^{(\kappa+1)}, \dots, q_{j_f}^{(f)}) - V(q_{j_1}^{(1)}, \dots, q_{j_f}^{(f)})
 \end{aligned} \tag{6.5}$$

It is easy to show that if V is separable

$$V(q_1, \dots, q_f) = V^{(1)}(q_1) + V^{(2)}(q_2) + \cdots + V^{(f)}(q_f) \tag{6.6}$$

then V_{JL} is given "exactly", *i.e.* by quadrature over the primitive grid.

CDVR works fine and often gives good results. Its numerical effort is described by $f \cdot N \cdot n^{f-1} + n^f$ potential evaluations. This is still within MCTDH scaling laws, but the pre-factor is high as a potential evaluation will require many operations. Hence in a CDVR calculation the evaluation of the potential often takes 95 – 99.5% of the total effort. That is a bit odd.

But the most important drawback of CDVR is that one cannot use mode combination, at least not straightforwardly. To arrive at two- (or multi-) dimensional grid points (x_κ, y_κ) and the associated two-dimensional localized functions one can solve the minimization problem

$$\langle \xi(x, y) | (\hat{x} - x_0)^2 + (\hat{y} - y_0)^2 | \xi(x, y) \rangle = \min \tag{6.7}$$

To be varied are the numbers x_0, y_0 and the functions ξ . In $1D$ one can show that a diagonalization solves the minimum problem. With this trick one can derive a $2D$ -DVR for the $2D$ -SPFs. However, it seems not to work so well, as there are almost no published results. Seemingly, for multi-dimensional comined SPFs there are too few quadrature points thus deteriorating the quality of the CMF quadrature.

²U. Manthe, *J. Chem. Phys.* **105**, 6989 (1996).

Chapter 7

Electronic States

Some small modifications of the MCTDH algorithm are required when the WF is to be propagated on several electronic states, *i.e.* when vibronic coupling becomes important

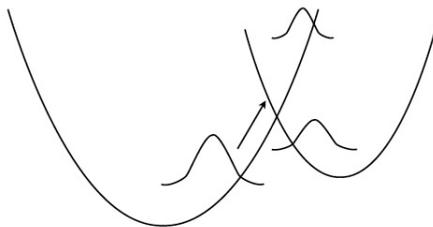


Figure 7.1: Wavepacket evolving on two coupled states.

One can modify the MCTDH ansatz straightforwardly by including the electronic state-labelling as additional coordinate

$$\Psi(q_1, \dots, q_f, \alpha, t) = \sum_{j_1}^{n_1} \cdots \sum_{j_f}^{n_f} \sum_{s=1}^{n_s} A_{j_1 \dots j_f s} \varphi_{j_1}^{(1)}(q_1, t) \cdots \varphi_{j_f}^{(f)}(q_f, t) \varphi_s^{(f+1)}(\alpha, t) \quad (7.1)$$

The coordinate α is discrete and $\varphi_s^{(f+1)}(\alpha, t)$ is hence a vector and not a function. But this is nothing new, all our variables are discrete, because we use DVRs.

There are usually only a few electronic states. This makes it reasonable to use a complete set of SPFs for the electronic degrees of freedom, *i.e.* as many SPFs as there are electronic states. Doing so, the SPFs become time-independent (because of the projector) and it is useful to choose

$$\varphi_s^{(f+1)}(\alpha, t) = \delta_{\alpha, s} \quad (7.2)$$

This allows us to write the WF in a more vivid form:

$$\Psi = \sum_{j_1}^{n_1} \cdots \sum_{j_f}^{n_f} \sum_{\alpha=1}^{n_s} A_{j_1 \dots j_f \alpha} \varphi_{j_1}^{(1)}(q_1, t) \cdots \varphi_{j_f}^{(f)}(q_f, t) |\alpha\rangle \quad (7.3)$$

This is the so called single set formalism. It is called "single-set" because there is one set of SPFs for all electronic states. The single-set formalism closely follows the MCTDH philosophy. In contrast, the *multi-set* formulation uses different sets of SPFs for each state

$$\Psi(q_1, \dots, q_f, \alpha, t) = \sum_{\alpha=1}^{n_s} \Psi^{(\alpha)}(q_1, \dots, q_f, t) |\alpha\rangle \quad (7.4)$$

where each component WF $\Psi^{(\alpha)}$ is expanded in MCTDH form

$$\Psi^{(\alpha)}(q_1, \dots, q_f, t) = \sum_{j_1^\alpha}^{n_1^\alpha} \cdots \sum_{j_f^\alpha}^{n_f^\alpha} A_{j_1^\alpha \dots j_f^\alpha}^{(\alpha)}(t) \varphi_{j_1^\alpha}^{(1, \alpha)}(q_1, t) \cdots \varphi_{j_f^\alpha}^{(f, \alpha)}(q_f, t) \quad (7.5)$$

The equations of motion must be generalized

$$i \dot{A}_J^{(\alpha)} = \sum_{\beta=1}^{n_s} \sum_L \mathcal{K}_{JL}^{(\alpha, \beta)} A_L^{(\beta)} \quad (7.6)$$

$$i \dot{\varphi}_j^{(\kappa, \alpha)} = (1 - P^{(\kappa, \alpha)}) (\rho^{(\kappa, \alpha)})_{jl}^{-1} \sum_{\beta=1}^{n_s} \sum_{k=1}^{n_\kappa} \mathcal{H}_{lk}^{(\kappa, \alpha, \beta)} \varphi_k^{(\kappa, \beta)} \quad (7.7)$$

with the obvious definitions

$$\mathcal{K}_{JL}^{(\alpha, \beta)} = \langle \Phi_J^{(\alpha)} | H^{(\alpha, \beta)} | \Phi_L^{(\beta)} \rangle \quad (7.8)$$

$$\mathcal{H}_{ji}^{(\kappa, \alpha, \beta)} = \langle \Psi_j^{(\kappa, \alpha)} | H^{(\alpha, \beta)} | \Psi_i^{(\kappa, \beta)} \rangle \quad (7.9)$$

The single-set formalism is of advantage if the dynamics in the different electronic states is similar, *e.g.* when the surfaces are almost parallel. The more complicated multi-set formalism is more efficient when the dynamics on the various diabatic states is rather different. In most cases multi-set is the preferred scheme.

Chapter 8

Initial state

As emphasized several times, using a time-dependent method requires to specify an initial state. The simplest choice is a Hartree product. The A-vector then becomes

$$A_{j_1 \dots j_f} = \delta_{j_1,1} \cdots \delta_{j_f,1} \quad (8.1)$$

hence a 1 at the first position and zero everywhere else. A more complicated A-vector can be specified through the keyword `A-coeff`. One specifies a few individual values of $A_{j_1 \dots j_f}$ all remaining entries are set to zero. Next we have to specify the initial SPFs. For the Heidelberg MCTDH package, the choices are:

- (1) Generalized Gaussians

$$\varphi(x) = N \exp(-\alpha (x - x_0)^2 + ip_0 x) \quad (8.2)$$

where α can be complex whereas x_0 and p_0 are real parameters.

The other SPFs of that DOF are generated by multiplying φ with x and Schmidt-orthogonalize to the lower functions. For a simple Gaussian to start with, this in fact produces the harmonic oscillator functions.

- (2) Legendre functions

$$P_l(\cos \theta) \quad (8.3)$$

and associated Legendre functions

$$P_j^m(\cos \theta) \quad (8.4)$$

These functions are then \mathcal{L}^2 normalized and may serve as initial functions for angular degrees of freedom.

- (3) Eigenfunctions of a 1D-Hamiltonian. This 1D-Hamiltonian has to be defined in the operator file. This operator is diagonalised when the keyword `eigenf` is set. The eigenfunctions are taken as SPFs.
- (4) Eigenfunctions of a mode-Hamiltonian. A mode (particle) Hamiltonian is diagonalised by a Lanczos algorithm when the keyword `meigenf` is set. The eigenfunctions are taken as SPFs.

Example: Inelastic $H_2 + H_2$ scattering:

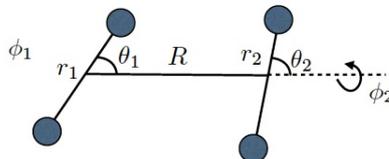


Figure 8.1: The $H_2 + H_2$ set of coordinates.

The H_4 system is described by 7 coordinates, $\phi_1, \theta_1, r_1, \phi_2, \theta_2, r_2$, and R . This is because we are working in a so-called E_c system rather than a body-fixed (BF) system. In BF, $\phi = 0$ by definition. The DoFs (θ_1, ϕ_1) and (θ_2, ϕ_2) are combined, because we want to use the two-dimensional DVRs KLeg or PLeg. The initial SPFs are the spherical harmonics:

$$\phi(\theta_i, \phi_i, t = 0) = Y_j^m(\theta_i, \phi_i) \sim P_j^m(\cos\theta_i) e^{im\phi_i} \quad \text{for } i = 1, 2 \quad (8.5)$$

where j and m denote the initial rotational quantum numbers of the diatomic subsystem. For $\varphi(r_1, t = 0)$ and $\varphi(r_2, t = 0)$ we take the eigenfunctions of the 1D-vibrational Hamiltonian

$$H_{vib} = -\frac{1}{2m} \frac{\partial^2}{\partial r^2} + \frac{j(j+1)}{2mr^2} + V_{H_2}(r) \quad (8.6)$$

and for $\varphi(R, t = 0)$ we use a Gaussian with momentum p_0

$$\varphi(R) = e^{-\alpha(R-R_0)^2} e^{-ip_0R} \quad (8.7)$$

For this case this is a very appropriate initial state.

For several other applications the initial state is an eigenstate, often the ground state, of another Hamiltonian (or electronic state), *e.g.* the photodissociation of NOCl. In this case one builds a Hartree product and relaxes it to the ground state or uses improved relaxation to obtain an excited state.

Finally, one often needs to multiply a MCTDH wavefunction with an operator to get an appropriate initial state. A typical example is the IR-spectroscopy. Here the initial state is

$$\hat{\mu} \cdot \Psi_0 \quad (8.8)$$

where Ψ_0 denotes the ground state and $\hat{\mu}$ the dipole operator.

MCTDH can do such an operation, keyword "operate", but this is a complicated iterative process, because the A-vector and the SPFs have to be modified. The working equations are derived through a VP. Let $\tilde{\Psi}$ and Ψ denote the WF to be operated and the final result, respectively:

$$\Psi = \hat{D}\tilde{\Psi} \quad (8.9)$$

Then the VP reads

$$\langle \delta\Psi_J | \Psi - \hat{D}\tilde{\Psi} \rangle = \delta \sum_{\kappa=1}^f \sum_{jl} \epsilon_{jl}^{(\kappa)} (\langle \varphi_j^{(\kappa)} | \varphi_l^{(\kappa')} \rangle - \delta_{jl}) \quad (8.10)$$

The right hand-side is introduced to ensure orthonormality of the SPFs. The $\epsilon_{jl}^{(\kappa)}$ are the so-called Lagrange multipliers.

Variation with respect to the coefficients yields ($\partial\Psi/\partial A_J = \Phi_J$)

$$\langle \Phi_J | \Psi - D\tilde{\Psi} \rangle = 0 \quad (8.11)$$

or

$$\boxed{A_J = \sum_L \langle \Phi_J | D | \tilde{\Phi}_L \rangle \tilde{A}_L} \quad (8.12)$$

Variation with respect to $\langle \varphi_j^{(\kappa)} |$ yields ($\partial\Psi/\partial\varphi_j^{(\kappa)} = \Psi_j^{(\kappa)}$)

$$\langle \Psi_j^{(\kappa)} | \Psi - \hat{D}\tilde{\Psi} \rangle = \sum_l \epsilon_{jl}^{(\kappa)} \varphi_l^{(\kappa)} \quad (8.13)$$

Since

$$\Psi = \sum_j \Psi_j^{(\kappa)} \varphi_j^{(\kappa)} \quad (8.14)$$

one finds

$$(\rho_{jl}^{(\kappa)} - \epsilon_{jl}^{(\kappa)}) \cdot \varphi_l^{(\kappa)} = \sum_L \langle \Psi_j^{(\kappa)} | D | \tilde{\Psi}_l^{(\kappa)} \rangle \tilde{\varphi}_l^{(\kappa)} \quad (8.15)$$

Rather than to determine those values of $\epsilon_{jl}^{(\kappa)}$ which keep the SPFs orthogonal, we drop the matrix $(\rho - \epsilon)$ and define

$$\tilde{\varphi}_j^{(\kappa)} = \sum_l \langle \Psi_j^{(\kappa)} | D | \tilde{\Psi}_l^{(\kappa)} \rangle \tilde{\varphi}_l^{(\kappa)} \quad (8.16)$$

The desired functions $\varphi_j^{(\kappa)}$ are then obtained by Schmidt orthogonalization of the $\tilde{\varphi}_j^{(\kappa)}$. This procedure is legitimate as only the space spanned by the SPFs matters. Orthogonal transformations among the SPFs are accounted for by the coefficients. The iteration reads:

(0)

$$\begin{aligned} \varphi_j^{(\kappa)(0)} &= \tilde{\varphi}_j^{(\kappa)} \\ A_j^{(0)} &= \sum_L \langle \Phi_J^{(0)} | D | \tilde{\Phi}_L \rangle \tilde{A}_L \end{aligned} \quad (8.17)$$

(1) for $i = 0, 1, 2, \dots$ do:

$$\tilde{\varphi}_j^{(\kappa)(i+1)} = \sum_l \langle \Psi_j^{(\kappa)(i)} | D | \tilde{\Psi}_l^{(\kappa)} \rangle \tilde{\varphi}_l^{(\kappa)} \quad (8.18)$$

(2) Gram-Schmidt orthogonalization of $\tilde{\varphi}_j^{(\kappa)}$ to obtain $\varphi_j^{(\kappa)}$.

(3)

$$A_J^{(i+1)} = \sum_L \langle \Phi_J^{(i+1)} | D | \tilde{\Phi}_L \rangle \tilde{A}_L \quad (8.19)$$

(4) **stop if**

$$1 - \text{Trace}\{P^{(\kappa)(i)} P^{(\kappa)(i+1)} \hat{\rho}^{(\kappa)(i+1)}\} \quad (8.20)$$

is smaller than some threshold. Here $P^{(\kappa)(i)}$ denotes the MCTDH projection at the i -th iteration and $\hat{\rho}^{(\kappa)(i)}$ the density operator at the i -th iteration.

(5) **next i**

Chapter 9

Representation of the potential

9.1 The Product form

We have already mentioned the quadrature problem. At each time-step we have to compute the matrix representation of the Hamiltonian

$$H_{JK} = \langle \Phi_J | H | \Phi_K \rangle \quad (9.1)$$

and the mean-fields

$$\langle H \rangle_{jl}^{(\kappa)} = \langle \Psi_j^{(\kappa)} | H | \Psi_l^{(\kappa)} \rangle \quad (9.2)$$

If one would do these integrals by straightforward quadrature over the primitive grid, one would have to run over N^f grid points for potential like operators and N^{2f} points for non-diagonal operators. For example

$$V_{JK} = \langle \Phi_J | V | \Phi_K \rangle = \sum_{i_1=1}^{N_1} \cdots \sum_{i_f=1}^{N_f} \varphi_{j_1}^{(1)*}(q_{i_1}^{(1)}) \cdots \varphi_{j_f}^{(f)*}(q_{i_f}^{(f)}) V(q_{i_1}^{(1)}, \dots, q_{i_f}^{(f)}) \varphi_{j_1}^{(1)}(q_{i_1}^{(1)}) \cdots \varphi_{j_f}^{(f)}(q_{i_f}^{(f)}) \quad (9.3)$$

And this integral has to be done for each J and K , hence n^{2f} times.

Example:

Let $f = 6$, $n = 6$ and $N = 32$.

One integral: $N^f = 32^6 = 10^9$ operations

Number of integrals: $n^{2f} 6^{12} = 2 \cdot 10^9$ operations

hence $\approx 10^{18}$ operations in total. This is impossible!

The trick is to write the Hamiltonian as a sum of products¹

$$H = \sum_{r=1}^s c_r h_r^{(1)} \cdots h_r^{(f)} \quad (9.4)$$

where $h_r^{(\kappa)}$ operates on the κ -th particle (combined mode) only.

If we now do the integral we find:

$$H_{JK} = \sum_{r=1}^s c_r \langle \varphi_{j_1}^{(1)} | h_r^{(1)} | \varphi_{j_1}^{(1)} \rangle \cdots \langle \varphi_{j_f}^{(f)} | h_r^{(f)} | \varphi_{j_f}^{(f)} \rangle \quad (9.5)$$

i.e. a sum of products of *one-dimensional* integrals. Doing all the H_{JK} integrals we can re-use the $\langle h_r^{(\kappa)} \rangle$ integrals. There are

$$s \cdot f \cdot n^2$$

1D integrals to be done. Hence

$$s \cdot f \cdot N \cdot n^2 \quad (9.6)$$

multiplications.

The final summation is a negligible amount of work. This is to be compared with the work of doing the integrals directly, *i.e.* $n^{2f} \cdot N^f$. Going back to our example: $f = 6$, $n = 6$ and $N = 32$, and assume $s = 14000$.

We find:

$$s \cdot f \cdot N \cdot n^2 \approx 10^8$$

$$n^{2f} \cdot N^f \approx 10^{18}$$

Hence we gain 10 orders of magnitude!

The question is, how realistic is a product form of the Hamiltonian? Fortunately KEOs are almost always of product form. For example NOCl (Fig.9.1):

$$T = -\frac{1}{2\mu_d} \frac{\partial^2}{\partial r_d^2} - \frac{1}{2\mu_v} \frac{\partial^2}{\partial r_v^2} - \frac{1}{2\mu_d} \frac{1}{r_d^2} \frac{1}{\sin\theta} \frac{\partial}{\partial\theta} \sin\theta \frac{\partial}{\partial\theta} - \frac{1}{2\mu_v} \frac{1}{r_v^2} \frac{1}{\sin\theta} \frac{\partial}{\partial\theta} \sin\theta \frac{\partial}{\partial\theta}$$

Potentials are sometimes given as polynomials. *E.g.* in the NOCl case

$$V(r_d, r_v, \theta) = \sum_{i,j,k} C_{i,j,k} (r_d - r_d^e)^i (r_v - r_v^e)^j \cos^k \theta \quad (\text{or } \cos(k\theta)) \quad (9.7)$$

¹ For particle operators, the expression reads:

$$H = \sum_{r=1}^s c_r h_r^{(1)} \cdots h_r^{(p)}$$

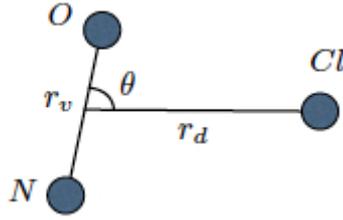


Figure 9.1: The Jacobi coordinates for NOCl.

Hence the product form is not as unusual as it may look at a first glance. For the general case, however, one needs an algorithm which brings a general potential to product form. POTFIT is such an algorithm.

9.2 The potfit algorithm

The most direct way to achieve a product form is an expansion of the potential in a product basis:

$$V^{\text{app}}(q_1, \dots, q_f) = \sum_{j_1=1}^{m_1} \cdots \sum_{j_f=1}^{m_f} C_{j_1 \dots j_f} v_{j_1}^{(1)}(q_1) \cdots v_{j_f}^{(f)}(q_f) \quad (9.8)$$

(Looks like a MCTDH expansion of a WF!) As we use DVRs we need to know the potential only at the grid points.

Let $q_i^{(\kappa)}$ denote the position of the i -th grid point of the κ -th grid. Then we define

$$V_{i_1, \dots, i_f} = V(q_{i_1}^{(1)}, \dots, q_{i_f}^{(f)}) \quad (9.9)$$

i.e. V_{i_1, \dots, i_f} denotes the value of the potential on the grid points.

The approximate potential on the grid is given by

$$V_{i_1, \dots, i_f}^{\text{app}} = \sum_{j_1=1}^{m_1} \cdots \sum_{j_f=1}^{m_f} C_{j_1 \dots j_f} v_{i_1 j_1}^{(1)} \cdots v_{i_f j_f}^{(f)} \quad (9.10)$$

where

$$v_{i_\kappa j_\kappa}^{(\kappa)} = v_{j_\kappa}^{(\kappa)}(q_{i_\kappa}^{(\kappa)}) \quad (9.11)$$

The single particle potentials (SPPs) are assumed to be orthogonal on the grid

$$\sum_{i=1}^{N_\kappa} v_{ij}^{(\kappa)} v_{il}^{(\kappa)} = \delta_{jl} \quad (9.12)$$

Throughout this chapter i and k label grid-points and j and l label SPPs. We can, of course, use mode combination. Then the SPPs are defined on multi-dimensional grids and f is to be replaced by p . The generalization is obvious.

To find the optimal coefficients and the optimal SPPs, we minimize

$$\Delta^2 = \sum_{i_1=1}^{N_1} \cdots \sum_{i_f=1}^{N_f} \left(V_{i_1 \dots i_f} - V_{i_1 \dots i_f}^{\text{app}} \right)^2 = \sum_I (V_I - V_I^{\text{app}})^2 \quad (9.13)$$

Minimizing Δ^2 by varying only the coefficients yields:

$$C_{j_1 \dots j_f} = \sum_{i_1=1}^{N_1} \cdots \sum_{i_f=1}^{N_f} V_{i_1 \dots i_f} v_{i_1 j_1}^{(1)} \cdots v_{i_f j_f}^{(f)} \quad (9.14)$$

hence the coefficients are given by overlap (as expected).

Plugging this into the expression for Δ^2 yields:

$$\Delta^2 = \|\mathbf{V}\|^2 - \|\mathbf{C}\|^2 = \sum_I V_I^2 - \sum_I C_I^2 \quad (9.15)$$

Therefore, one has to optimize the (orthonormal) SPPs such that $\|\mathbf{C}\|^2$ becomes maximal. The solution of this variational problem is difficult. It is numerically very demanding and likely to converge to a local minimum.

We take a shortcut and define potential density matrices as:

$$\rho_{kk'}^{(\kappa)} = \sum_{I^\kappa} V_{I^\kappa} V_{I^\kappa} \quad (9.16)$$

We then diagonalize the densities $\rho^{(\kappa)}$ and take the eigenvectors with the largest eigenvalues as SPPs. (Note $\rho^{(\kappa)}$ is positive semi-definite. Hence all eigenvalues $\lambda_j \geq 0$). The procedure is known to yield the optimal SPPs for a two dimensional case. For higher dimensions the error is not optimal but sufficiently close to optimal.

9.2.1 Contraction

Contraction over one mode is another very useful trick to reduce the numerical effort. We can perform one sum once for all. Let us, for the sake of simplicity, contract over the first DOF:

$$D_{i_1 j_2 \dots j_f} := \sum_{j_1=1}^{N_1} C_{j_1 \dots j_f} v_{i_1 j_1}^{(1)} \quad (9.17)$$

The potential is then given by

$$V_{i_1, \dots, i_f}^{\text{app}} = \sum_{j_2=1}^{m_1} \cdots \sum_{j_f=1}^{m_f} D_{i_1 j_2 \dots j_f} v_{i_2 j_2}^{(2)} \cdots v_{i_f j_f}^{(f)} \quad (9.18)$$

Hence, rather than m^f terms we have only $m^{(f-1)}$ terms. Moreover, if we increase m_1 to N_1 , which increases the accuracy, one notices that C of that

index is a unitary transformation of V which is then transformed back. Hence there is no transformation at all and D is given by

$$D_{i_1 j_2 \dots j_f} = \sum_{i_2 \dots i_f} V_{i_1 \dots i_f} v_{i_2 j_2}^{(2)} \dots v_{i_f j_f}^{(f)} \quad (9.19)$$

Turning to a coordinate representation, we write the contracted potential more vividly

$$V^{\text{app}}(q_1, \dots, q_f) = \sum_{j_2=1}^{m_2} \dots \sum_{j_f=1}^{m_f} D_{j_2 \dots j_f}(q_1) v_{j_2}^{(2)}(q_2) \dots v_{j_f}^{(f)}(q_f) \quad (9.20)$$

Of course we can contract over any degree of freedom, not necessarily over the first one. In general one will contract over that mode which otherwise has the largest m . Note that when using contraction the coefficient vector C and the SPPs of the contracted mode are not computed, see Eq. (9.19).

9.2.2 Error estimate

Letting ν denote the contracted mode, the error can be bounded by

$$\frac{\Lambda}{f-1} \leq \Delta_{\text{opt}}^2 \leq \Delta^2 \leq \Lambda \quad (9.21)$$

where

$$\Lambda = \sum_{\substack{\kappa=1 \\ \kappa \neq \nu}}^f \sum_{j=m_\kappa+1}^{N_\kappa} \lambda_j^{(\kappa)} \quad (9.22)$$

and where Δ^2 denotes the potfit \mathcal{L}^2 -error and Δ_{opt}^2 the \mathcal{L}^2 -error one would obtain after a full optimization of the SPPs. Note that the error is determined by the eigenvalues of the neglected SPPs. In particular, for $m_\kappa = N_\kappa$ one recovers the exact potential on the grid.

The last inequality of Eq. (9.21) tells us how to choose the expansion orders, m_κ , for a given error to be tolerated. The inequality in the middle is trivial and the last inequality shows that the error bound Λ is at most $(f-1)$ times larger than the optimal error Δ_{opt}^2 .

Proof of Eq. (9.21)

In appendix D of the MCTDH review² is shown that

$$\begin{aligned} \Delta^2 &= \sum_{\substack{\text{neglected} \\ \text{terms}}} |C_J|^2 = \sum_{j_1=m_1+1}^{N_1} \sum_{j_2=1}^{N_2} \dots \sum_{j_f=1}^{N_f} |C_{j_1 \dots j_f}|^2 \\ &+ \sum_{j_1=1}^{N_1} \sum_{j_2=m_2+1}^{N_2} \dots \sum_{j_f=1}^{N_f} |C_{j_1 \dots j_f}|^2 \\ &+ \dots + \\ &+ \sum_{j_1=1}^{N_1} \sum_{j_2=1}^{N_2} \dots \sum_{j_f=m_f+1}^{N_f} |C_{j_1 \dots j_f}|^2 \end{aligned} \quad (9.23)$$

²M. H. Beck, A. Jäckle, G. A. Worth and H.-D. Meyer, Physics Reports **324**, 1 (2000).

where we have assumed that the coefficients $C_{j_1 \dots j_f}$ are evaluated for $1 \leq j_\kappa \leq N_\kappa$ although in potfit they are used only for $1 \leq j_\kappa \leq m_\kappa$. We can enlarge the sum by letting j_κ always run up to N_κ . Hence

$$\Delta^2 \leq \sum_{\kappa=1}^f \sum_{I^\kappa} \sum_{j=m_\kappa+1}^{N_\kappa} |C_{I_j^\kappa}|^2 = \sum_{\kappa=1}^f \sum_{j=m_\kappa+1}^{N_\kappa} \lambda_j^{(\kappa)} \quad (9.24)$$

because

$$\tilde{\rho}_{jj'}^{(\kappa)} = \sum_{J^\kappa}^{\{N\}} C_{I_j^\kappa} C_{I_{j'}^\kappa} = \delta_{jj'} \lambda_j^{(\kappa)} \quad (9.25)$$

Here J runs up to N . Note that the C 's are just the unitarily transformed V 's.³

This proves the right-hand-side inequality. Because we use contraction and we are complete in the contracted mode, we may restrict the sums over κ in Eq. (9.24) to $\kappa \neq \nu$, where ν denotes the contracted mode. Next, we set all $m_\nu = N_\nu$ except for the κ -th degree of freedom. The \mathcal{L}^2 -error is then

$$^{(\kappa)}\Delta^2 = \sum_{j=m_\kappa+1}^{N_\kappa} \lambda_j^{(\kappa)} \quad (9.26)$$

and as we may collect all DOFs $\neq \kappa$ into one mode, we are essentially treating a 2-mode problem which is optimal

$$^{(\kappa)}\Delta^2 = ^{(\kappa)}\Delta_{\text{opt}}^2 \quad (9.27)$$

On the other hand, we have

$$^{(\kappa)}\Delta_{\text{opt}}^2 \leq \Delta_{\text{opt}}^2 \quad (9.28)$$

because for $^{(\kappa)}\Delta^2$ we keep more terms. Finally, as κ is arbitrary we arrive at

$$\begin{aligned} \frac{1}{f-1} \sum_{\substack{\kappa=1 \\ \kappa \neq \nu}}^f \sum_{j=m_\kappa+1}^{N_\kappa} \lambda_j^{(\kappa)} &\leq \max_{\kappa \neq \nu} \sum_{j=m_\kappa+1}^{N_\kappa} \lambda_j^{(\kappa)} \leq \max_{\kappa} ^{(\kappa)}\Delta_{\text{opt}}^2 \\ &\leq \Delta_{\text{opt}}^2 \leq \Delta^2 \leq \sum_{\substack{\kappa=1 \\ \kappa \neq \nu}}^f \sum_{j=m_\kappa+1}^{N_\kappa} \lambda_j^{(\kappa)} \end{aligned} \quad (9.29)$$

where ν denotes the contracted mode.

³ To show this

$$\begin{aligned} \tilde{\rho}_{jj'}^{(\kappa)} &= \sum_{J^\kappa}^{\{N\}} C_{I_j^\kappa} C_{I_{j'}^\kappa} \\ &= \sum_{J^\kappa} (\boldsymbol{\Omega}^T \mathbf{V})_{J_j^\kappa} (\boldsymbol{\Omega}^T \mathbf{V})_{J_{j'}^\kappa} \\ &= \sum_{I^\kappa} \sum_{i, i'} V_{I_i^\kappa} v_{ij}^{(\kappa)} V_{I_{i'}^\kappa} v_{i'j'}^{(\kappa)} \\ &= \sum_{i, i'} v_{ij}^{(\kappa)} \rho_{ii'}^{(\kappa)} v_{i'j'}^{(\kappa)} = (\mathbf{v}^{(\kappa)})^T \boldsymbol{\rho}^{(\kappa)} \mathbf{v}^{(\kappa)}_{j, j'} \\ &= \rho_{jj'}^{\text{diag}} = \delta_{jj'} \lambda_j^{(\kappa)} \end{aligned}$$

where the orthogonality of the SPPs along the grid has been used.

9.2.3 Weights

The inclusion of weights is often very important, because one does not need a uniform accuracy. The accuracy may be low when the potential is high, simply because the WF does not go there. On the other hand, we need a high accuracy near the minimum and at transition states (saddle points). Hence, we want to minimise:

$$\Delta_w^2 = \sum_I w_I^2 (V_I - V_I^{\text{app}})^2 \quad (9.30)$$

The inclusion of separable weights

$$w_I = w_{i_1}^{(1)} \dots w_{i_f}^{(f)} \quad (9.31)$$

is very simple. One simply potfits $w_I \cdot V_I$ and then divide the SPPs by the weights

$$v_i^{(\kappa)} \rightarrow v_i^{(\kappa)} / w_i^{(\kappa)} \quad (9.32)$$

However, separable weights are in general not very helpful. The inclusion of non-separable weights is very difficult. There appear matrices like

$$\langle v_{j_1}^{(1)} \dots v_{j_f}^{(f)} | w | v_{j_1}^{(1)} \dots v_{j_f}^{(f)} \rangle \quad (9.33)$$

which have to be inverted. As their dimension is the full total grid size, this is impossible.

There is a nice trick to emulate non-separable weights. Assume there is a reference potential V^{ref} such that

$$(V_I - V_I^{\text{app}}) w_I^2 = V_I^{\text{ref}} - V_I^{\text{app}} \quad (9.34)$$

holds. Then, we simply potfit V^{ref} and hence minimize

$$\sum_I (V_I^{\text{ref}} - V_I^{\text{app}})^2 \quad (9.35)$$

which in turn is equal to

$$\sum_I w_I^2 (V_I - V_I^{\text{app}})^2 \quad (9.36)$$

i.e. the weighted sum which we want to minimize! Obviously, V^{ref} is given by

$$V_I^{\text{ref}} = w_I^2 V_I + (1 - w_I^2) V_I^{\text{app}} \quad (9.37)$$

However, as V_I^{app} is unknown, we have to use an iterative process:⁴

$$(1) V_I^{\text{app} (0)} = \text{potfit}(V)$$

(2) for $n = 1, \dots, n_{\text{max}}$ do

$$V_I^{\text{ref} (n)} = w_I^2 V_I + (1 - w_I^2) V_I^{\text{app} (n-1)}$$

$$V_I^{\text{app} (n)} = \text{potfit}(V_I^{\text{ref} (n)})$$

⁴Actually, we loop over the modes and update V^{ref} after each new SPP(m).

(3) next n

The question is, of course, does this process converge? In fact, one may multiply w_I by some positive constant. The final converged result must not change. One can show that for sufficiently small w_I the iteration will always converge and for sufficiently large w_I it will always diverge.

We always adopted the concept of a relevant region, *i.e.*

$$w_I = w(q_I) = \begin{cases} 1 & \text{if } q_I \in \text{relevant region,} \\ 0 & \text{else.} \end{cases}$$

The relevant region is often defined by an energy criterium

$$w_I = w(q_I) = \begin{cases} 1 & \text{if } V_I \leq E_{rel}, \\ 0 & \text{if } V_I > E_{rel}. \end{cases}$$

but it may contain restrictions on the coordinate as well. We also tried to replace w_I by $\alpha \cdot w_I$. The iterative process always converges for $0 < \alpha \leq 1$ and always diverges for $\alpha > 2$. The convergence is slower for smaller α . An improved convergence speed can be obtained for $\alpha \approx 1.5, 1.6, \dots$

9.2.4 Computational effort

Doing the integrals

$$\langle \Phi_J | V | \Phi_L \rangle \quad (9.38)$$

directly requires N^f multiplications. Using potfit one needs $s \cdot f \cdot N$ multiplications with $s = m^{f-1}$. Hence the gain is⁵

$$\text{gain}_{\text{CPU}} = \frac{1}{f} \left(\frac{N}{m} \right)^{f-1}$$

This is already a considerable gain if $m \leq N/3$ and $f \geq 3$. If we have to perform the integrals for all J and L we have to do n^{2f} such integrals because J and L can take n^f different values. With potfit, however, we need to do $f \cdot n^2$ 1D integrals, store them, and finally do the sum of products of these integrals. The effort for the latter operation is negligible. Doing all the 1D integrals takes:

$$m^{f-1} \cdot f \cdot N \cdot n^2 \quad (9.39)$$

multiplications. Comparing this to $N^f \cdot n^{2f}$ yields the gain:

$$\text{gain}_{\text{CPU}} = \frac{1}{f} \left(\frac{N}{m} \right)^{f-1} n^{2(f-1)} \quad (9.40)$$

which is a large number already for $f \geq 3$. Example, for $f = 4$, $N = 21$, $m = 7$, and $n = 6$, $\text{gain}_{\text{CPU}} = 315000$.

⁵ When using mode combination

$$\text{gain}_{\text{CPU}} = \frac{1}{p} \left(\frac{N}{m} \right)^{p-1}$$

9.2.5 Memory consumption

As the potential is diagonal (we always assume a DVR), it consumes N^f data points. A potfit with contraction reads

$$V_{i_1 \dots i_f}^{\text{app}} = \sum_{j_2=1}^{m_2} \cdots \sum_{j_f=1}^{m_f} D_{j_2 \dots j_f}(q_1) v_{j_2}^{(2)}(q_2) \cdots v_{j_f}^{(f)}(q_f) \quad (9.41)$$

Hence there are

$$\underbrace{m^{f-1} \cdot N}_D + \underbrace{(f-1) \cdot m \cdot N}_{v's} \quad (9.42)$$

data points. For $f \geq 3$ the second part is negligible. Hence

$$\text{gain}_{\text{mem}} = \frac{N^f}{m^{f-1} \cdot N} = \left(\frac{N}{m}\right)^{f-1} \quad (9.43)$$

For the small example system we have just discussed ($f = 4$, $N = 21$, $m = 7$), we have a memory gain of 27. But turning to a slightly larger system: $f = 6$, $N = 24$, $m = 6$, we find

$$\begin{aligned} \text{gain}_{\text{mem}} &= 1024 \\ \text{Full potential} &= 1.5\text{GB} \\ \text{Potfit} &= 1.5\text{MB} \end{aligned}$$

This is a very considerable reduction in memory demand!

Let us go even further and assume a really large system with $f = 12$, $N = 12$. Here we adopt mode-combination and combine 3 DOF into one particle: $d = 3$, $p = 4$, $N_{\text{particle}} = N_{\text{DOF}}^3 = 1728$.

Let us assume we need $m = 45$ for convergence. Then there are

$$s = m^{p-1} = 45^3 = 91125 \quad \text{terms} \quad (9.44)$$

and the memory consumption is

$$m^{p-1} \cdot N_{\text{particle}} = 1.575 \times 10^8 \text{ points} = 1.17\text{GB} \quad (9.45)$$

The full potential, however, requires

$$N^f = 12^{12} = 8.9 \cdot 10^{12} \text{ points} = 65\text{TB} \quad (9.46)$$

65 TB is impossible, but 1.17 GB is doable. Hence potfit solves also a memory problem! This is crucial for larger systems.

Unfortunately, we cannot potfit a $12D$ system. In potfit we have to run over the full product grid to determine the coefficients or the density matrices. This limits the use of potfit to systems with less than 10^9 grid points (*e.g.* 6D or 7D)

9.2.6 Summary

- (i) POTFIT, although not fully optimal, is a variational method. If the number of terms increases, the error has to go down. For $m_\kappa = N_\kappa$ one recovers the exact potential at the grid points. Defining:

$$\Lambda = \sum_{\substack{\kappa=1 \\ \kappa \neq \nu}}^f \sum_{j=m_\kappa+1}^{N_\kappa} \lambda_j^{(\kappa)} \quad (9.47)$$

we can bound the potfit error by

$$\frac{1}{f-1} \Lambda \leq \Delta_{\text{opt}}^2 \leq \Delta^2 \leq \Lambda \quad (9.48)$$

- (ii) The inclusion of weights is often important. It can significantly lower the rms error⁶, which in this case is the error within the relevant region. However, due to the iterative character this makes potfit slow.
- (iii) The operation

$$\sum_I V_{JI} \cdot A_I \quad (9.49)$$

which is part of

$$i\dot{A}_J = \sum_I H_{JI} A_I \quad (9.50)$$

requires $s \cdot f \cdot n^{f+1}$ operations for a potfitted potential rather than n^{2f} operations. This is another advantage of the product structure.

9.3 Cluster expansion

One way out of the potfit dilemma, (potfit can handle only total grid sizes up to 10^9), is an expansion called n-mode representation, or cut-HDMR or cluster expansion. The potential is represented by a hierarchical expansion of one-body terms, two-body terms, etc.

$$\begin{aligned} V(q_1, q_2, \dots, q_f) &= V^{(0)} \\ &+ \sum_{j=1}^f V_j^{(1)}(q_j) + \sum_{j < k} V_{jl}^{(2)}(q_j, q_k) + \sum_{j < k < l} V_{jkl}^{(2)}(q_j, q_k, q_l) + \dots \end{aligned} \quad (9.51)$$

The expansion is exact if we include all clusters up to the f -th order. The hope is, of course, that the series can be truncated after few terms.

⁶The rms is defined as

$$\text{rms} = \sqrt{\Delta^2 / \sum_I w_I^2} = \sqrt{\Delta^2 / N_{\text{tot}}} \quad \text{if } w_I = 1 \quad N_{\text{tot}} = \prod_{\kappa} N_{\kappa}$$

The clusters $V^{(n)}$ can be determined in different ways, the easiest one is with respect to a reference point

$$\mathbf{q}^{(0)} = (q_1^{(0)}, q_2^{(0)}, \dots, q_f^{(0)}) \quad (9.52)$$

usually the GS geometry. Then

$$V^{(0)} = V(\mathbf{q}^{(0)}) \quad (9.53)$$

$$V_j^{(1)}(q_j) = V(q_1^{(0)}, \dots, q_{j-1}^{(0)}, q_j, q_{j+1}^{(0)}, \dots, q_f^{(0)}) - V^{(0)} \quad (9.54)$$

$$\begin{aligned} V_{j,k}^{(2)}(q_j, q_k) &= V(q_1^{(0)}, \dots, q_j, \dots, q_k, \dots, q_f^{(0)}) \\ &\quad - (V^{(0)} + V_j^{(1)}(q_j) + V_k^{(1)}(q_k)) \end{aligned} \quad (9.55)$$

Note that the cluster vanishes, if at least one of the coordinates is at the reference point.

$$V_j^{(1)}(q_j^{(0)}) = 0$$

$$V_{jk}^{(2)}(q_j, q_k^{(0)}) = V_{jk}^{(2)}(q_j^{(0)}, q_k) = 0$$

$$V_{jkl}^{(3)}(q_j, q_k, q_l^{(0)}) = V_{jkl}^{(3)}(q_j, q_k^{(0)}, q_l) = V_{jkl}^{(3)}(q_j^{(0)}, q_k, q_l) = 0$$

From that follows that the n-th order cluster expansion

$$V_n(q_j, \dots, q_f) = V^{(0)} + \dots + \sum_j V_{j\dots}^{(n)} \quad (9.56)$$

is *exact* if at most n coordinates are not at the reference point.

The clusters can then be potfitted as they are usually smaller than 6D. One problem is that there are so many clusters. There are

$$\binom{f}{n} = \frac{f!}{n!(f-n)!} \quad (9.57)$$

clusters of n -th order. For $f=12$ we obtain

$$\begin{array}{cccccccc} \text{n} & 0 & 1 & 2 & 3 & 4 & 5 & 6 \\ \binom{f}{n} & 1 & 12 & 66 & 220 & 495 & 792 & 924 \end{array}$$

A way out of this dilemma is mode combination. We do the cluster expansion in combined modes

$$V(Q_1, \dots, Q_p) = V^{(0)} + \sum_{j=1}^p V_j^{(1)}(Q_p) + \dots + \sum V_{jl}^{(n)} + \dots \quad (9.58)$$

with $f = 12$, $d = 2$ and $p = 6$, we could go to second or third order in the particles which would be up to 4th or 6th order in the DOFs. However, we have only a selection of the high order DOF clusters. With

$$Q_1 = (q_1, q_2), \quad Q_2 = (q_3, q_4), \quad Q_3 = (q_5, q_6) \quad (9.59)$$

and second order mode expansion one obtains

$$\begin{aligned}
 V(q_1, q_2, \dots, q_f) = & V^{(0)} + V^{(1)}(q_1, q_2) + V^{(1)}(q_3, q_4) + V^{(1)}(q_5, q_6) + \\
 & V^{(2)}(q_1, q_2, q_3, q_4) + V^{(2)}(q_1, q_2, q_5, q_6) + V^{(2)}(q_3, q_4, q_5, q_6)
 \end{aligned} \tag{9.60}$$

we do not miss any second order DOF term, *e.g.* $V(q_1, q_5)$ is contained in $V(q_1, q_2, q_5, q_6)$. In second order we are complete! However, we miss the 3rd order DOF terms $V(q_1, q_3, q_5)$, *i.e.* all terms where each coordinate is out of a different particle. Similarly, we miss $V(q_1, q_2, q_3, q_5)$, etc. If the mode combination scheme is good, *i.e.* combines the strongly correlated DOFs, the neglected terms will be small. The neglected terms will, of course, be recovered when including high orders in expansion (9.58). This, however is often out of the reach for numerical reasons. One usually takes all second order particle based clusters and a selection of third order clusters into account.

Chapter 10

Complex absorbing potentials (CAPs)

When dealing with a bound system, there is no problem with the grids. Turning to study dissociation or scattering processes one notices that some of the grids may become very long. The minimal propagation time is determined by the time needed for the slow components of the WF to leave the interaction region. Within this time interval the fast components of the WP may have travelled a long distance requiring a long grid.

A solution to this problem is provided by complex absorbing potentials (CAP). A CAP is a negative imaginary potential, usually written as

$$-i\eta W(r) = -i\eta(r - r_c)^n \theta(r - r_c)$$

where $W(r)$ is a non-negative real function, often of the indicated monomial form, n is 2,3, or 4, η is a strength parameter, and r_c denotes the position where the CAP is switched on.

Let us investigate how a CAP changes the norm

$$\frac{d}{dt}\|\Psi\|^2 = \frac{d}{dt}\langle\Psi|\Psi\rangle = \langle\dot{\Psi}|\Psi\rangle + \langle\Psi|\dot{\Psi}\rangle \quad (10.1)$$

$$= \langle -iH\Psi|\Psi\rangle + \langle\Psi|-iH\Psi\rangle \quad (10.2)$$

$$= i\langle\Psi|H^\dagger - H|\Psi\rangle \quad (10.3)$$

with

$$H = H_0 - i\eta W \quad H_0 = H_0^\dagger \quad (10.4)$$

$$H^\dagger = H_0 + i\eta W \quad W = W^\dagger \quad (10.5)$$

follows

$$\frac{d}{dt}\|\Psi\|^2 = -2\eta \langle\Psi|W|\Psi\rangle \quad (10.6)$$

$$\frac{d}{dt}\|\Psi\| = -\eta \frac{\langle\Psi|W|\Psi\rangle}{\|\Psi\|} \quad (10.7)$$

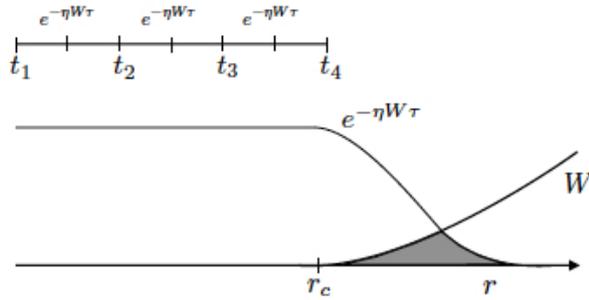


Figure 10.1: Decrease of the norm of a wavepacket being annihilated by a complex absorbing potential starting at r_c .

Hence the norm of the WF decreases when the wavepacket enters the CAP. We want to inspect in more detail how the CAP annihilates the wavepacket. We know the formal solution of the Schrödinger equation

$$\begin{aligned}\Psi(t + \tau) &= e^{(-iH_0 - \eta W)\tau} \Psi(t) \\ &= e^{-iH_0 \frac{\tau}{2}} e^{-\eta W \tau} e^{-iH_0 \frac{\tau}{2}} \Psi(t) + O(\tau^3)\end{aligned}\quad (10.8)$$

i.e. in the middle of each time step, the WF is multiplied by $e^{-\eta W \tau}$, a half Gaussian when $W \sim r^2$ (Fig. 10.1).

When is it legitimate to use a CAP? Of course, it is legitimate to annihilate the outgoing parts when they do not enter the computation of the desired observables. For instance, when computing the autocorrelation function

$$a(t) = \langle \Psi(0) | \Psi(t) \rangle \quad (10.9)$$

then it is clear that those parts of $\Psi(t)$ which do not overlap with $\Psi(0)$ and will never return to overlap with $\Psi(0)$ may be annihilated (Fig. 10.2).

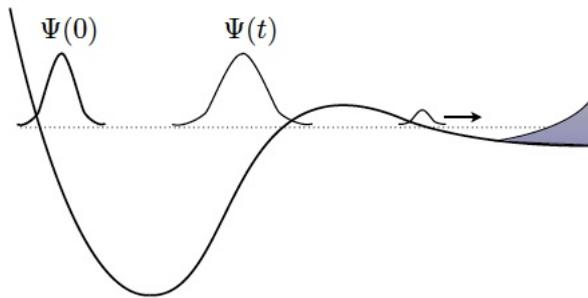


Figure 10.2: Example of the correct location of a CAP.

What happens, if we do not introduce a CAP but still work with a small grid? At the end of the grid one automatically introduces a wall, *i.e.* a grid or

a finite basis set puts the system into a box. Due to the wall, the outgoing part of the WP will be reflected and will again overlap with $\Psi(0)$. This destroys the correctness of the autocorrelation function. Hence a CAP is a great invention. However, it does not only annihilate a WF, but also reflects. The reflection is a non-ideal behaviour of a CAP.

The origin of the reflection is easy to understand. It is related to the Heisenberg uncertainty principle. We change the form of the WF, *i.e.* its coordinate distribution. But this implies that one also changes the momentum distribution which is just the Fourier-transform of the coordinate representation and this means reflection. To see this, let us turn to the time-independent picture.

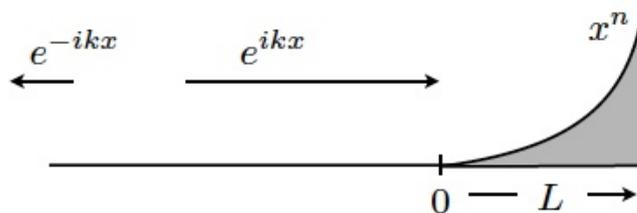


Figure 10.3: Undesired behaviour of a CAP.

At energy E the WF must be a linear combination of e^{ikx} and e^{-ikx} where $E = k^2/2m$. Hence

$$\Psi(x) \sim e^{ikx} - R e^{-ikx} \quad \text{for } x < 0 \quad (10.10)$$

where R denotes the reflection coefficient. If we put an infinite wall at $x = 0$, we have total reflection ($R = 1$):

$$\Psi(x) \sim e^{ikx} - e^{-ikx} \sim \sin kx \quad \Psi(0) \equiv 0 \quad (10.11)$$

Using scattering theory and semiclassical arguments one can derive approximate formulas

$$R^2 = \left| \frac{n!}{2^{n+2}} \right|^2 \cdot \frac{\eta^2}{E^2 \cdot k^2} = \left| \frac{n!}{2^{n+2}} \right|^2 \cdot \left(\frac{\hbar^2}{2m} \right)^n \cdot \frac{\eta^2}{E^{n+2}} \quad (10.12)$$

$$T^2 = \exp\left(-\frac{\eta L^{n+1} \cdot 2m}{k(n+1)}\right) = \exp\left(-\frac{\eta W(L)}{E} \cdot \frac{k \cdot L}{n+1}\right) \quad (10.13)$$

and of course one wants $T^2 + R^2 \ll 1$. This requires weak (η small) and long (L large) CAPs. (The above formulas are evaluated by the MCTDH script `plcap`).

Note that $k \cdot L = 2\pi$ is equivalent to say that L equals one de-Broglie wavelength. A CAP should be at least two de-Broglie wavelengths long.

Chapter 11

Filter-Diagonalization (FD)

We know that the exact autocorrelation function of a bound system is given by (see Chapter 1):

$$a(t) = \sum_n |c_n|^2 e^{-iE_n t} \quad (11.1)$$

with

$$c_n = \langle \Psi_n | \Psi(0) \rangle \text{ and } H\Psi_n = E\Psi_n \quad (11.2)$$

The intensities $|c_n|^2$ and the eigenenergies E_n can be obtained by a Fourier transform of $a(t)$, but this requires that $a(t)$ is given for all times, otherwise we have a finite resolution.

But if there is only a finite number, say 100 or less, of lines with noticeable intensity, then one may simply fit the right hand side of Eq. (11.2) to the first short period of the autocorrelation function $a(t)$. However, this is a non-linear fit, which complicates the analysis.

The FD-method accomplishes such a fit by linear algebra. Within some energy window one defines a usually equally spaced energy grid $\epsilon_1 < \epsilon_2 < \dots < \epsilon_n$ (Fig. 11.1). For each point of the energy grid one computes the filtered states:

$$\Psi_{E_k} = \int g(t) \tilde{\Psi}(t) e^{i\epsilon_k t} dt \quad (11.4)$$

Such a state is a superposition of exact eigenstates with energy near ϵ_k , $g(t)$ is a window function introduced in Section 1.3.1. We take the filtered states as basis set and compute the Hamiltonian matrix

$$H_{jk} = \langle \Psi_{E_j} | H | \Psi_{E_k} \rangle \quad (11.5)$$

as well as the overlap matrix

$$\Theta_{jk} = \langle \Psi_{E_j} | \Psi_{E_k} \rangle \quad (11.6)$$

which is needed because the filtered states are not orthonormal.

¹Note that

$$\Psi_E \sim \delta(H - E) \Psi(0) \sim \int_{-\infty}^{\infty} e^{iEt} \Psi(t) dt \quad (11.3)$$

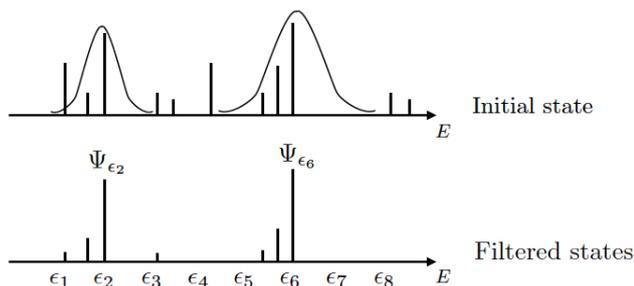


Figure 11.1: Filter diagonalization. The upper picture shows a spectral decomposition (Power Spectrum) of an initial state and, symbolically, the filtering envelopes. The lower figure shows the spectral decomposition of two filtered states.

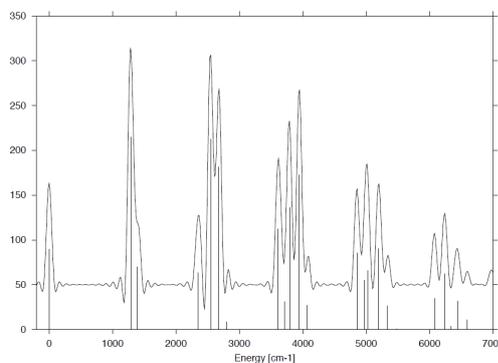


Figure 11.2: The vibrational spectrum of CO₂ as obtained by Fourier transform of the autocorrelation function and by FD using the same autocorrelation function. For better visibility, the Fourier spectrum is shifted upwards by 50 units.

Then we solve the generalized eigenvalue problem

$$\mathbf{H}\mathbf{b}_n = \tilde{E}_n \mathbf{\Theta}\mathbf{b}_n \quad (11.7)$$

where \tilde{E}_n is our approximation to the exact eigenenergy E_n . The approximate eigenvectors are given by

$$\Psi_{E_n} = \sum_j b_{jn} \Psi_{\epsilon_j} \quad (11.8)$$

The method works because in practice one never computes the filtered states Ψ_{ϵ_j} . The overlap-matrix $\mathbf{\Theta}$ and the Hamiltonian matrix \mathbf{H} can be directly calculated from the autocorrelation function $a(t)$

$$\Theta_{jk} = \text{Re} \int_0^T G(E_j - E_k, \tau) a(\tau) e^{i\frac{E_j + E_k}{2}\tau} d\tau \quad (11.9)$$

$$H_{jk} = \text{Re} \int_0^T i \dot{G}(E_j - E_k, \tau) a(\tau) e^{i\frac{E_j + E_k}{2}\tau} d\tau \quad (11.10)$$

where G is a known but complicated function which depends on the window function g (see J. Chem. Phys., **109**,3730 (1998)). Hence FD is just another but more efficient form to extract the information from the autocorrelation function $a(t)$. The FD algorithm is more efficient than the Fourier transform of the autocorrelation function, because it "knows" that the spectra consist of discrete lines of positive intensity.

The usefulness of the filter-diagonalization approach is demonstrated in Fig. 11.2 where a spectrum obtained by Fourier-transform of the autocorrelation function is compared with the stick spectrum obtained by filter-diagonalization using the same autocorrelation function.

Appendix A

Discrete Variable Representation (DVR)

A.1 Introduction

On a computer a function has to be represented by a *finite* set of numbers, *i.e.* by a vector. To achieve this discretization, one may use basis sets representations (Spectral methods)

$$\Psi = \sum_{j=1}^N a_j \phi_j, \quad a_j = \langle \phi_j | \Psi \rangle$$
$$\Psi \rightarrow \mathbf{a} = (a_1, a_2, \dots, a_N)^T$$

or grid representations

$$x_\alpha, \alpha = 1, \dots, N \text{ grid points}$$

$$\Psi(x) \rightarrow (\Psi(x_1), \dots, \Psi(x_N))^T = (\Psi_1, \dots, \Psi_N)^T = \{\Psi_\alpha\}$$

The great advantage of grid methods is that the application of the in general complicated potential operator is very simple

$$(\hat{V}\Psi)_\alpha = (\hat{V}\Psi)(x_\alpha) = V(x_\alpha) \cdot \Psi(x_\alpha) \quad (\text{A.1})$$

For doing matrix-elements by quadrature over the grid, we need weights in addition

$$\langle \Psi | \Phi \rangle = \sum_{\alpha=1}^n w_\alpha \Psi^*(x_\alpha) \Phi(x_\alpha) \quad (\text{A.2})$$

But the most difficult problem are the differential operators, because there is no differentiable function anymore. If one interpolates the points *locally*, one arrives at the finite-difference formulas, *e.g.*

$$\Psi''(x_\alpha) \approx \frac{1}{h^2} (\Psi(x_{\alpha+1}) - 2\Psi(x_\alpha) + \Psi(x_{\alpha-1})) \quad (\text{A.3})$$

(local quadratic interpolation of an equidistant grid, where h is the grid spacing). Unfortunately, the finite differences are not too accurate!

A.2 Discrete Variable Representation

A DVR, like a basis representation, is a global approximation of high accuracy. To arrive at a DVR we diagonalize the matrix representation of the coordinate operator

$$Q_{jk} = \langle \varphi_j | \hat{x} | \varphi_k \rangle \quad (\text{A.4})$$

$$\mathbf{Q} = \mathbf{U} \mathbf{X} \mathbf{U}^\dagger \quad \text{Eigenvector matrix} \quad (\text{A.5})$$

$$\mathbf{X}_{\alpha\beta} = x_\alpha^2 \delta_{\alpha\beta} \quad \text{Eigenvalue matrix} \quad (\text{A.6})$$

If \mathbf{Q} is tri-diagonal, then the weights are given as

$$w_\alpha^{1/2} = \frac{U_{k,\alpha}}{\varphi_k^*(x_\alpha)} \quad (\text{A.7})$$

independent of k !¹

Hence we have a quadrature rule, and the matrix elements

$$\langle \varphi_j | \varphi_k \rangle = \sum_{\alpha=1}^N w_\alpha \varphi_j^*(x_\alpha) \varphi_k(x_\alpha) = \delta_{\alpha\beta} \quad (\text{A.8})$$

$$\langle \varphi_j | \hat{x} | \varphi_k \rangle = \sum_{\alpha=1}^N w_\alpha \varphi_j^*(x_\alpha) x_\alpha \varphi_k(x_\alpha) = Q_{jk} \quad (\text{A.9})$$

are *exact* in quadrature.

Next we introduce DVR-functions defined as

$$\chi_\alpha(x) = \sum_{j=1}^N \varphi_j(x) U_{j\alpha} \quad (\text{A.10})$$

The DVR functions are, of course, orthonormal

$$\langle \chi_\alpha | \chi_\beta \rangle = \delta_{\alpha\beta} \quad (\text{A.11})$$

and they behave like δ -functions on the grid

$$\chi_\alpha(x_\beta) = w_\alpha^{-1/2} \delta_{\alpha\beta} \quad (\text{A.12})$$

Potential matrix elements are now simple

$$\begin{aligned} \langle \chi_\alpha | V | \chi_\beta \rangle &= \sum_{\gamma=1}^N w_\gamma \chi_\alpha^*(x_\gamma) V(x_\gamma) \chi_\beta(x_\gamma) \\ &= \sum_{\gamma=1}^N w_\gamma w_\alpha^{-1/2} w_\beta^{-1/2} \delta_{\alpha\gamma} \delta_{\beta\gamma} V(x_\gamma) \\ &= V(x_\gamma) \delta_{\alpha\beta} \end{aligned} \quad (\text{A.13})$$

¹This is called a proper DVR. The quadrature is then of Gaussian quality. If \mathbf{Q} is not tri-diagonal one speaks of an improper DVR. An improper DVR does not provide weights. Here we assume proper DVRs but the CDVR method (see Chapter 6) is built on an improper DVR.

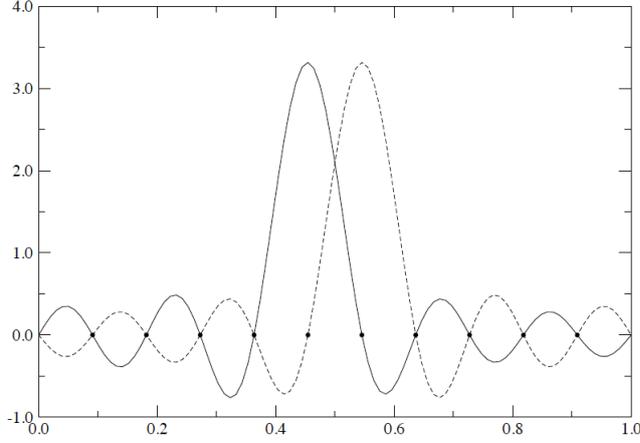


Figure A.1: Two sine DVR functions (solid and dashed lines) centred at two consecutive DVR points. Note that the functions are strictly zero at all DVR points (black dots) but one, which labels the function.

This is the DVR approximation. It is an approximation because the matrix element is done by quadrature, not exactly. Similarly

$$\langle \chi_\alpha | \Psi \rangle = \sum_{\gamma=1}^N w_\gamma \chi_\alpha^*(x_\gamma) \Psi(x_\gamma) = w_\alpha^{-1/2} \Psi(x_\alpha) \quad (\text{A.14})$$

connecting grid and basis set representations.

We represent the WF by its values at the grid points times square root of weights

$$\Psi(x) \rightarrow \mathbf{\Psi} = (w_1^{1/2} \Psi(x_1), \dots, w_N^{1/2} \Psi(x_N))^T \quad (\text{A.15})$$

which is both, a grid and a spectral representation (see Eq. A.14, pseudo-spectral methods). Integrals are now simple

$$\langle \Psi | \Phi \rangle = \sum_{\alpha=1}^N w_\alpha \Psi_\alpha^*(x_\alpha) \Phi(x_\alpha) = \sum_{\alpha=1}^N \Psi_\alpha^* \Phi_\alpha = \mathbf{\Psi}^* \cdot \mathbf{\Phi} \quad (\text{A.16})$$

In fact, one almost never needs the weights, as they are build into the WF. Only for plotting a WF or generating an initial WF from an analytic expression, weights are needed.

To derive the kinetic energy operator for the DVR-grid representations, we start considering its basis set representation (finite basis representation, FBR).

$$T_{jk}^{\text{FBR}} = \langle \varphi_j | \hat{T} | \varphi_k \rangle \quad (\text{A.17})$$

where we assume that the matrix elements can be done analytically.

The DVR-representation is then given by a unitary transformation

$$T_{\alpha\beta}^{\text{DVR}} = \langle \chi_\alpha | \hat{T} | \varphi_\beta \rangle = (\mathbf{U}^\dagger \mathbf{T}^{\text{FBR}} \mathbf{U})_{\alpha\beta} \quad (\text{A.18})$$

Remarks:

- (i) a DVR determines the volume element to be used: dr , $r^2 dr$, $\sin\theta d\theta$, etc.
- (ii) a DVR determines the boundary conditions.
- (iii) the potential should be smoother than the WF to ensure that the DVR error is small, (no hard walls). The variational property is destroyed because the potential matrix elements are not evaluated exactly, *i.e.* computed eigenvalues are not necessarily upper bounds to the exact ones.
- (iv) for smooth potentials and not too few grid points, the DVR error (*cf.* Eq. (A.13)) is in general smaller or of the same order than the basis set truncation error.