Python On Resonance (PyOR)

Everybody can simulate NMR

Author: Vineeth Thalakottoor

Email: vineethfrancis.physics@gmail.com

Tutorial 11: Evolution of Density Matrix in Liouville Space (Part 3)

In this tutorial you will see how to evolve the desnity matrix in time by solving Liouville-Von Neumann equation in Liouville Space of six spin half system (ethanol).

Load Python packages and define path to the source file "PythonOnResonance.py"

In [28]:
```
pathSource = '/media/HD2/Vineeth/PostDoc_Simulations/Github/PyOR_G/Source'
```

In [29]:
```
from IPython.display import display, HTML
display(HTML("<style>.container { width:100% !important; }</style>"))
import sys
sys.path.append(pathSource)

import PythonOnResonance as PyOR

import time
import numpy as np
import matplotlib.pyplot as plt
from matplotlib import rc
%matplotlib notebook
import sympy as sp
from sympy import *
```

Generating Spin System

In [30]:
```
"""
Define Spin quantum numbers of your spins in "Slist1".
Slist1[0] is spin of first particle and Slist1[1] is spin of second particle.
""";

Slist1 = [1/2,1/2,1/2,1/2,1/2,1/2]
```

In [31]:
```
"""
Define Planck constant equals 1.
Because NMR spectroscopists are more interested to write Energy in frequency units.
if False then hbarEQ1 = hbar
""";

hbarEQ1 = True
```

In [32]:
```
"""
Generate Spin Operators
""";

System = PyOR.Numerical_MR(Slist1,hbarEQ1)

"""
Sx, Sy and Sz Operators
""";
Sx,Sy,Sz = System.SpinOperator()

"""
S+ and S- Operators
""";
Sp,Sm = System.PMoperators(Sx,Sy)
```

Zeeman Hamiltonian in Lab Frame

In [33]:
```
"""
Gyromagnetic Ratio
Gamma = [Gyromagnetic Ratio spin 1, Gyromagnetic Ratio spin 1, ...]
""";
Gamma = [System.gammaH1,System.gammaH1,System.gammaH1,System.gammaH1,System.gammaH1,System

"""
Define the field of the spectromter, B0 in Tesla.
"""
B0 = 9.4

"""
Define the chemical Shift of individual spins
Offset = [chemical Shift spin 1, chemical Shift spin 1, ..]
"""
Offset = [100,100,100,500,500,1000] # Offset frequency in Hz

"""
Function "LarmorF" give the list Larmor frequencies of individual spins in lab frame
"""
LarmorF = System.LarmorFrequency(Gamma,B0,Offset)

Hz = System.Zeeman(LarmorF,Sz)
```

```
Larmor Frequency in MHz:  [-400.22811765 -400.22811765 -400.22811765 -400.22851765 -400.22
851765
 -400.22901765]
```

Initialize Density Matrix

In [34]:
```
"""
We will generate Initial Density Matrix in two ways:
First we will generate a density matrix as we prefer say, Sz.
Second we will create density matrix at thermal equlibrium

First Case
""";

Thermal_DensMatrix = False

if Thermal_DensMatrix:
    Hz_EnUnit = System.Convert_FreqUnitsTOEnergy(Hz)
    HT_approx = False # High Temperature Approximation is False
```

```
    T = 300 # Temperature in Kelvin
    rho_in = System.EqulibriumDensityMatrix(Hz_EnUnit,T,HT_approx)
    rhoeq = rho_in.copy()
else:
    rho_in = np.sum(Sz,axis=0) # Initial Density Matrix
    rhoeq = np.sum(Sz,axis=0)  # Equlibrium Density Matrix
    print("Trace of density metrix = ", np.trace(rho_in))
```

```
Trace of density metrix =  0j
```

Zeeman Halitonian in Rotating Frame

In [35]:

```
OmegaRF = [-System.gammaH1*B0,-System.gammaH1*B0,-System.gammaH1*B0,-System.gammaH1*B0,-Sy
Hzr = System.Zeeman_RotFrame(LarmorF, Sz, OmegaRF)
```

J Coupling Hamiltonian

In [36]:

```
'''
Define J couplings between individual spins
'''
Jlist = np.zeros((len(Slist1),len(Slist1)))
Jlist[0][3] = 7
Jlist[0][4] = 7
Jlist[1][3] = 7
Jlist[1][4] = 7
Jlist[2][3] = 7
Jlist[2][4] = 7
Jlist[3][5] = 5
Jlist[4][5] = 5
Hj = System.Jcoupling_Weak(Jlist,Sz)
```

Converting to Liouvillian

In [37]:

```
Hz_L = System.CommutationSuperoperator(Hz)
Hzr_L = System.CommutationSuperoperator(Hzr)
Hj_L = System.CommutationSuperoperator(Hj)
rho_in_L = System.Vector_L(rho_in)
rhoeq_L = System.Vector_L(rhoeq)
```

Pulse

In [38]:

```
"""
Rotate the magnetization about Y-axis, by an angle theta.
""";
pulse_angle = 90.0
rho_L = System.Rotate_L(rho_in_L,pulse_angle,np.sum(Sy,axis=0))
```

Relaxation Constant

In [39]:

```
'''
Define Relaxation superoperator
''';
R1 = 5
R2 = 5
```

```
R = R2 * np.ones(64)
"""
Options: "No Relaxation", "Phenomenological"
""";
Rprocess = "Phenomenological"

R_L = System.Relaxation_L(Rprocess,R,Sx,Sy,Sz,Sp,Sm)
```

Evolution of Density Matrix

In [40]:

```
dt = 0.00025
AQ = 3.0
Npoints = int(AQ/dt)
print("Number of points in the simulation", Npoints)

"""
option for solver, "method": "Unitary Propagator", "Relaxation" or "ODE Solver"
"""
method = "Relaxation"

start_time = time.time()
t, rho_t = System.Evolution_L(rhoeq_L,rho_L,Sx,Sy,Hzr_L + Hj_L - 1j * R_L,dt,Npoints,metho
end_time = time.time()
timetaken = end_time - start_time
print("Total time = %s seconds " % (timetaken))
```

```
Number of points in the simulation 12000
Total time = 55.52332258224487 seconds
```

Expectation value

In [41]:

```
EXP_T = np.sum(Sx,axis=0) + 1j * np.sum(Sy,axis=0)
EXP_Z = np.sum(Sz,axis=0)

LEXP_T = System.Detection_L(EXP_T)
LEXP_Z = System.Detection_L(EXP_Z)

t, Mp = System.Expectation_L(rho_t,LEXP_T,dt,Npoints)
t, Mz = System.Expectation_L(rho_t,LEXP_Z,dt,Npoints)
```

Fourier Transform

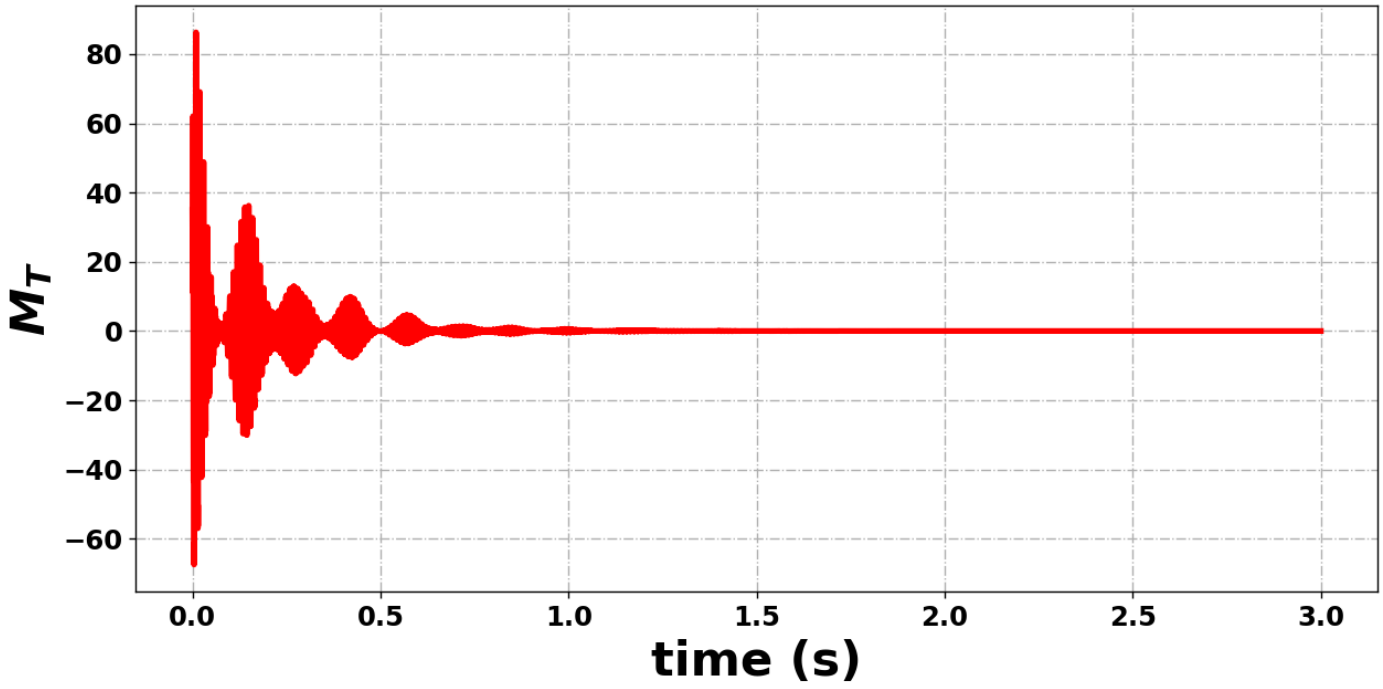
In [42]:

```
fs = 1.0/dt
freq, spectrum = System.FourierTransform(Mp,fs,1)
```

Plotting

In [43]:

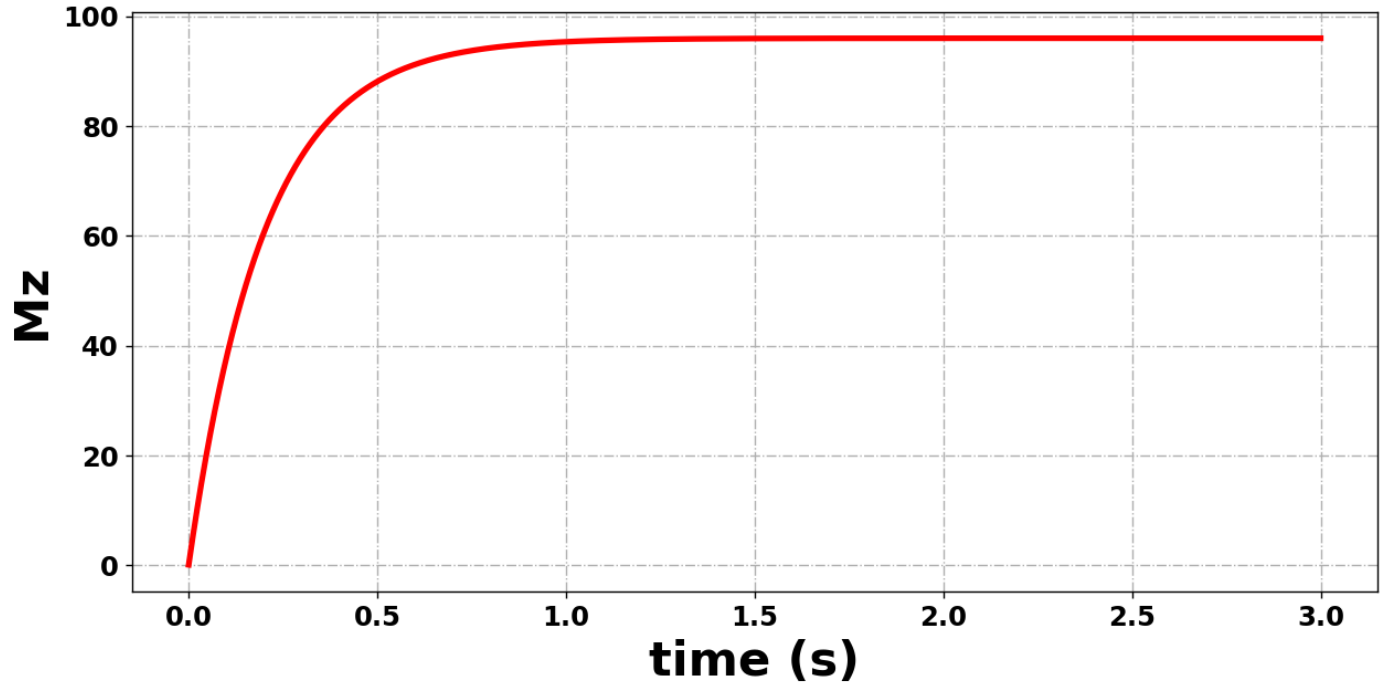
```
System.Plotting(3,t,Mp,"time (s)",r"$M_{T}$","red")
```




```
/opt/anaconda3/lib/python3.9/site-packages/numpy/core/_asarray.py:102: ComplexWarning: Cas
ting complex values to real discards the imaginary part
  return array(a, dtype, copy=False, order=order)
No handles with labels found to put in legend.
```

In [44]:

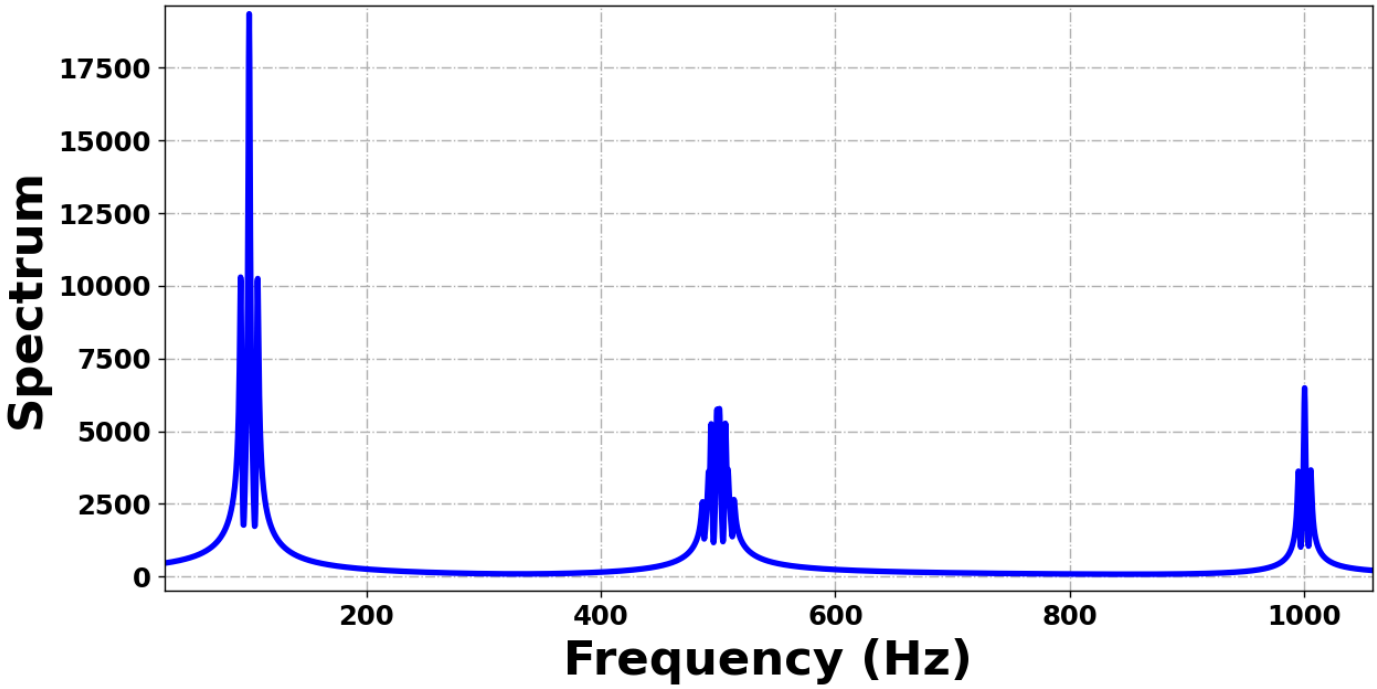
```
System.Plotting(4,t,Mz,"time (s)","Mz","red")
```




```
/opt/anaconda3/lib/python3.9/site-packages/numpy/core/_asarray.py:102: ComplexWarning: Cas
ting complex values to real discards the imaginary part
  return array(a, dtype, copy=False, order=order)
No handles with labels found to put in legend.
```

In [45]:

```
PH0 = -45.0
spectrum_PH0 = System.PhaseAdjust_PH0(spectrum,PH0)
System.Plotting(5,freq,np.absolute(spectrum_PH0),"Frequency (Hz)","Spectrum","blue")
```




```
No handles with labels found to put in legend.
```

Any suggestion? write to me

If you see something is wrong please write to me, so that the PyOR can be error free.

vineethfrancis.physics@gmail.com

In [ ]: