2-spin

Heisenberg Model

标准模型

$$H = J\sum_{<i,j>} \mathbf{S}_i \cdot \mathbf{S}_j \tag{1}$$

$$展开：H = J\sum(S_i^x S_j^x + S_i^y S_j^y + S_i^z S_j^z)$$

Using a basis $\{|\uparrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle, |\downarrow\downarrow\rangle\}$ for two spins the matrix representation of one 2-spin term is

$$\begin{pmatrix} J_{ij}/4 & 0 & 0 & 0 \\ 0 & -J_{ij}/4 & J_{ij}/2 & 0 \\ 0 & J_{ij}/2 & -J_{ij}/4 & 0 \\ 0 & 0 & 0 & J_{ij}/4 \end{pmatrix}. \tag{4.5}$$

H

4x4 double

	1	2	3	4
1	0.2500	0	0	0
2	0	-0.2500	0.5000	0
3	0	0.5000	-0.2500	0
4	0	0	0	0.2500

AFM

D

4x4 double

	1	2	3	4
1	-0.7500	0	0	0
2	0	0.2500	0	0
3	0	0	0.2500	0
4	0	0	0	0.2500

```
GS =

        0
   0.7071
  -0.7071
        0
```

FM

D

4x4 double

	1	2	3	4
1	-0.2500	0	0	0
2	0	-0.2500	0	0
3	0	0	-0.2500	0
4	0	0	0	0.7500

```
GS =

     1
     0
     0
     0
```

Heisenberg Model

标准模型

$$H = J\sum_{<i,j>} \mathbf{S}_i \cdot \mathbf{S}_j \tag{1}$$

展开： $H = J\sum(S_i^x S_j^x + S_i^y S_j^y + S_i^z S_j^z)$

2-spin

XXZ model

$$H = \left[\frac{1}{2}(S_1^+ \otimes S_2^- + S_1^- \otimes S_2^+) + \Delta S_1^z \otimes S_2^z\right] \tag{27}$$

```
% XXZ 参数:
Delta = 1;
```

AFM

D

4x4 double

	1	2	3	4
1	-0.7500	0	0	0
2	0	0.2500	0	0
3	0	0	0.2500	0
4	0	0	0	0.2500

```
GS =

        0
   0.7071
  -0.7071
        0
```

```
% XXZ 参数:
Delta = 0.5;
```

D

4x4 double

	1	2	3	4
	-0.6250	0	0	0
	0	0.1250	0	0
	0	0	0.1250	0
	0	0	0	0.3750

D GS

4x1 double

	1
1	0
2	0.7071
3	-0.7071
4	0

```
% XXZ 参数:
Delta = 2.0;
```

D

4x4 double

	1	2	3	4
	-1	0	0	0
	0	0	0	0
	0	0	0.5000	0
	0	0	0	0.5000

GS

4x1 double

	1
1	0
2	0.7071
3	-0.7071
4	0

XXZ model

$$H=\left[\frac{1}{2}(S_1^{+}\otimes S_2^{-}+S_1^{-}\otimes S_2^{+})+\Delta S_1^{z}\otimes S_2^{z}\right] \tag{27}$$

2-spin

AFM

```
% XXZ 参数:
Delta = 1;
```

D

4x4 double

	1	2	3	4
1	-0.7500	0	0	0
2	0	0.2500	0	0
3	0	0	0.2500	0
4	0	0	0	0.2500

```
GS =

         0
    0.7071
   -0.7071
         0
```

```
% XXZ 参数:
Delta = 2.0;
```

D

4x4 double

	1	2	3	4
	-1	0	0	0
	0	0	0	0
	0	0	0.5000	0
	0	0	0	0.5000

GS

4x1 double

	1
1	0
2	0.7071
3	-0.7071
4	0

```
% XXZ 参数:
Delta = 0.5;
```

D

4x4 double

	1	2	3	4
	-0.6250	0	0	0
	0	0.1250	0	0
	0	0	0.1250	0
	0	0	0	0.3750

D GS

4x1 double

	1
1	0
2	0.7071
3	-0.7071
4	0

FM

```
% XXZ 参数:
Delta = 1;
```

D

4x4 double

	1	2	3	4
1	-0.2500	0	0	0
2	0	-0.2500	0	0
3	0	0	-0.2500	0
4	0	0	0	0.7500

```
GS =

     1
     0
     0
     0
```

```
% XXZ 参数:
Delta = 2.0;
```

4x4 double

	1	2	3	4
1	-0.5000	0	0	0
2	0	-0.5000	0	0
3	0	0	0	0
4	0	0	0	1

```
GS =

     1
     0
     0
     0
```

```
% XXZ 参数:
Delta = 0.5;
```

	1	2	3	4
	-0.3750	0	0	0
	0	-0.1250	0	0
	0	0	-0.1250	0
	0	0	0	0.6250

```
GS =

         0
   -0.7071
   -0.7071
         0
```

Heisenberg Model

标准模型

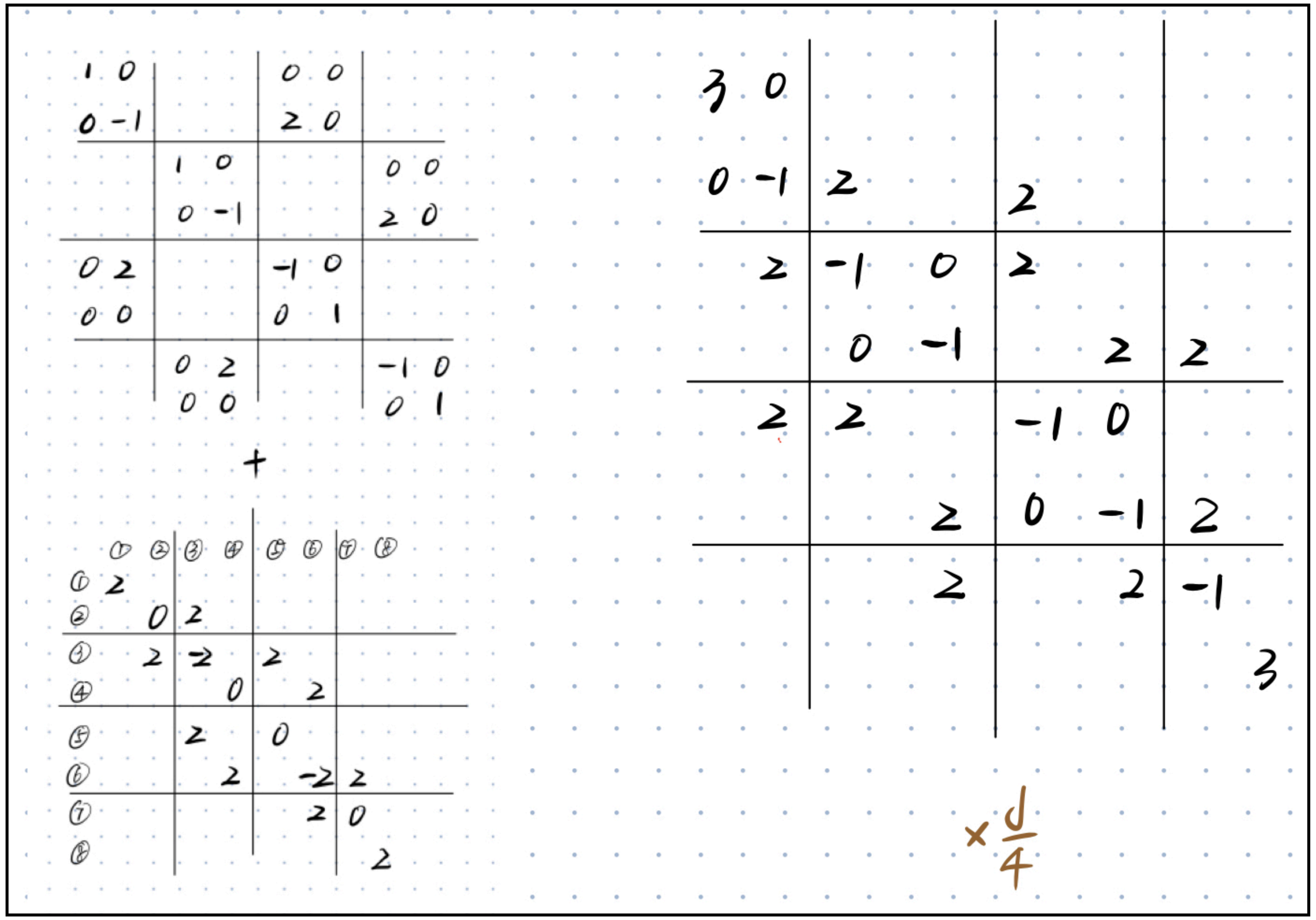
$$H = J\sum_{<i,j>} \mathbf{S}_i \cdot \mathbf{S}_j \tag{1}$$

展开： $H = J\sum(S_i^x S_j^x + S_i^y S_j^y + S_i^z S_j^z)$

3-spin

H =

$$\begin{matrix} 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 & 2 & 0 & 0 & 0 \\ 0 & 2 & -1 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 2 & 2 & 0 \\ 0 & 2 & 2 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & -1 & 2 & 0 \\ 0 & 0 & 0 & 2 & 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 \end{matrix}$$



XXZ model Delta=1时同样对得上

8×8 H矩阵:

$$H_1 = H_{old} \otimes I$$

$$\begin{bmatrix} 1 & & & \\ & -1 & 2 & \\ & 2 & -1 & \\ & & & 1 \end{bmatrix} \otimes \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$= \begin{array}{c|cc|cccc|cc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline 1 & 1 & 0 & & & & & & \\ 2 & 0 & 1 & & & & & & \\ \hline 3 & & & -1 & 0 & 2 & 0 & & \\ 4 & & & 0 & -1 & 0 & 2 & & \\ \hline 5 & & & 2 & 0 & -1 & 0 & & \\ 6 & & & 0 & 2 & 0 & -1 & & \\ \hline 7 & & & & & & & 1 & 0 \\ 8 & & & & & & & 0 & 1 \end{array} \qquad H_1$$

$$H_2 = I \otimes H_{old}$$

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \otimes \begin{bmatrix} 1 & & & \\ & -1 & 2 & \\ & 2 & -1 & \\ & & & 1 \end{bmatrix}$$

$$\begin{array}{c|cccc|cccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline 1 & 1 & & & & & & & \\ 2 & & -1 & 2 & & & & & \\ 3 & & 2 & -1 & & & & & \\ 4 & & & & 1 & & & & \\ \hline 5 & & & & & 1 & & & \\ 6 & & & & & & -1 & 2 & \\ 7 & & & & & & 2 & -1 & \\ 8 & & & & & & & & 1 \end{array} \qquad H_2$$

$$\begin{array}{c|cc|cccc|cc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline 1 & 1 & 0 & & & & & & \\ 2 & 0 & 1 & & & & & & \\ \hline 3 & & & -1 & 0 & 2 & 0 & & \\ 4 & & & 0 & -1 & 0 & 2 & & \\ \hline 5 & & & 2 & 0 & -1 & 0 & & \\ 6 & & & 0 & 2 & 0 & -1 & & \\ \hline 7 & & & & & & & 1 & 0 \\ 8 & & & & & & & 0 & 1 \end{array} + \begin{array}{c|c|cc|cc|cc|c} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline 1 & 1 & & & & & & & \\ 2 & & -1 & 2 & & & & & \\ \hline 3 & & 2 & -1 & & & & & \\ 4 & & & & 1 & & & & \\ \hline 5 & & & & & 1 & & & \\ 6 & & & & & & -1 & 2 & \\ \hline 7 & & & & & & 2 & -1 & \\ 8 & & & & & & & & 1 \end{array}$$

$$\begin{array}{c|cc|cc|cc|cc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline 1 & 2 & & & & & & & \\ 2 & & 0 & 2 & & & & & \\ \hline 3 & & 2 & -2 & & 2 & & & \\ 4 & & & & 0 & & 2 & & \\ \hline 5 & & & 2 & & 0 & & & \\ 6 & & & & 2 & & -2 & 2 & \\ \hline 7 & & & & & & 2 & 0 & \\ 8 & & & & & & & & 2 \end{array}$$

$$S^- = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \qquad S^+ = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \qquad \sigma^z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$H_3: \quad I_2 \otimes S_3^{z,\pm} \qquad \begin{bmatrix} 1 & \\ & 1 \end{bmatrix} \otimes \cdots$$

$$\begin{array}{cc|cc} 0/0/1 & 0/1/0 & & \\ 1/0/0 & 0/0/-1 & & \\ \hline & & 0/0/1 & 0/1/0 \\ & & 1/0/0 & 0/0/-1 \end{array}$$

$$S^+ \otimes I \otimes S^- \qquad S^- \otimes I \otimes S^+ \qquad S^z \otimes I \otimes S^z$$

$$2\times \left[\begin{array}{c|c} 0 & \begin{array}{cc|c} 0\ 0 & \\ 1\ 0 & \\ \hline & 0\ 0 \\ & 1\ 0 \end{array} \\ \hline 0 & 0 \end{array}\right] + 2\times \left[\begin{array}{c|c} 0 & 0 \\ \hline \begin{array}{c|c} 0\ 1 & \\ 0\ 0 & \\ \hline & 0\ 1 \\ & 0\ 0 \end{array} & 0 \end{array}\right] + \left[\begin{array}{c|c} \begin{array}{c|c} 1\ 0 & \\ 0\ -1 & \\ \hline & 1\ 0 \\ & 0\ -1 \end{array} & 0 \\ \hline 0 & \begin{array}{c|c} -1\ 0 & \\ 0\ +1 & \\ \hline & -1\ 0 \\ & 0\ +1 \end{array} \end{array}\right]$$

$$\begin{array}{cc|cc|cc|cc} 1 & 0 & & & 0 & 0 & & \\ 0 & -1 & & & 2 & 0 & & \\ \hline & & 1 & 0 & & & 0 & 0 \\ & & 0 & -1 & & & 2 & 0 \\ \hline 0 & 2 & & & -1 & 0 & & \\ 0 & 0 & & & 0 & 1 & & \\ \hline & & 0 & 2 & & & -1 & 0 \\ & & 0 & 0 & & & 0 & 1 \end{array} \qquad H_3$$

手解

$$\begin{array}{cc|cc|cc|cc} 1 & 0 & & & 0 & 0 & & \\ 0 & -1 & & & 2 & 0 & & \\ \hline & & 1 & 0 & & & 0 & 0 \\ & & 0 & -1 & & & 2 & 0 \\ \hline 0 & 2 & & & -1 & 0 & & \\ 0 & 0 & & & 0 & 1 & & \\ \hline & & 0 & 2 & & & -1 & 0 \\ & & 0 & 0 & & & 0 & 1 \end{array}$$

$$+$$

$$\begin{array}{c|cc|cc|cc|cc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline 1 & 2 & & & & & & & \\ 2 & & 0 & 2 & & & & & \\ \hline 3 & & 2 & -2 & & 2 & & & \\ 4 & & & & 0 & & 2 & & \\ \hline 5 & & & 2 & & 0 & & & \\ 6 & & & & 2 & & -2 & 2 & \\ \hline 7 & & & & & & 2 & 0 & \\ 8 & & & & & & & & 2 \end{array}$$

$$\begin{array}{cc|cc|cc|cc} 3 & 0 & & & & & & \\ 0 & -1 & 2 & & 2 & & & \\ \hline & 2 & -1 & 0 & 2 & & & \\ & & 0 & -1 & & 2 & 2 & \\ \hline & 2 & 2 & & -1 & 0 & & \\ & & & 2 & 0 & -1 & 2 & \\ \hline & & & 2 & & 2 & -1 & \\ & & & & & & & 3 \end{array} \times \frac{J}{4}$$

加入纵场项：

$$H=\left[\frac{1}{2}(S_1^+\otimes S_2^-+S_1^-\otimes S_2^+)+\Delta S_1^z\otimes S_2^z\right]+h_b(S_1^z\otimes I_2)+h_b(I_1\otimes S_2^z)\quad(28)$$

2-spin

核对手解形式：

2-spin 加入纵场

$$h_b\cdot \overset{1,\,-1}{S_1^z}\otimes I+h_b\cdot I\otimes \overset{1,\,1}{S_2^z}$$

$$\frac{1}{4}\times\begin{bmatrix}1&&&\\&-1&2&\\&2&-1&\\&&&1\end{bmatrix}+\begin{bmatrix}h_b&&&\\&h_b&&\\&&-h_b&\\&&&-h_b\end{bmatrix}+\begin{bmatrix}h_b&&&\\&-h_b&&\\&&h_b&\\&&&-h_b\end{bmatrix}$$

$$\frac{1}{4}\qquad\begin{bmatrix}2h_b&&&\\&0&&\\&&0&\\&&&-2h_b\end{bmatrix}\times\frac{1}{2}\ (\sigma\to S)\Rightarrow\begin{bmatrix}h_b&&&\\&0&&\\&&0&\\&&&-h_b\end{bmatrix}\checkmark$$

(用σ表示)

$$\frac{1}{4}-1=-\frac{3}{4}$$

H

4x4 double

	1	2	3	4
1	0.5000	0	0	0
2	0	-0.2500	0.5000	0
3	0	0.5000	-0.2500	0
4	0	0	0	0

```
H = 4*H;
```

H

4x4 double

	1	2	3	4
1	2	0	0	0
2	0	-1	2	0
3	0	2	-1	0
4	0	0	0	0

对得上

说明一下手解形式：最左边矩阵是无纵场且提出J/4的，

只有打勾的纵场矩阵是用S矩阵的正确表示（意味着比sigma矩阵表示差1/2倍）

然后令h=1/4,两个相加之后乘上4倍（把J/4这项消掉，矩阵元就是整数加减方便看）

纵场的检验： 3-spin

H

8x8 double

	1	2	3	4	5	6	7	8
1	1.5000	0	0	0	0	0	0	0
2	0	0	0.5000	0	0.5000	0	0	0
3	0	0.5000	0	0	0.5000	0	0	0
4	0	0	0	-0.5000	0	0.5000	0.5000	0
5	0	0.5000	0.5000	0	0	0	0	0
6	0	0	0	0.5000	0	-0.5000	0.5000	0
7	0	0	0	0.5000	0	0.5000	-0.5000	0
8	0	0	0	0	0	0	0	0

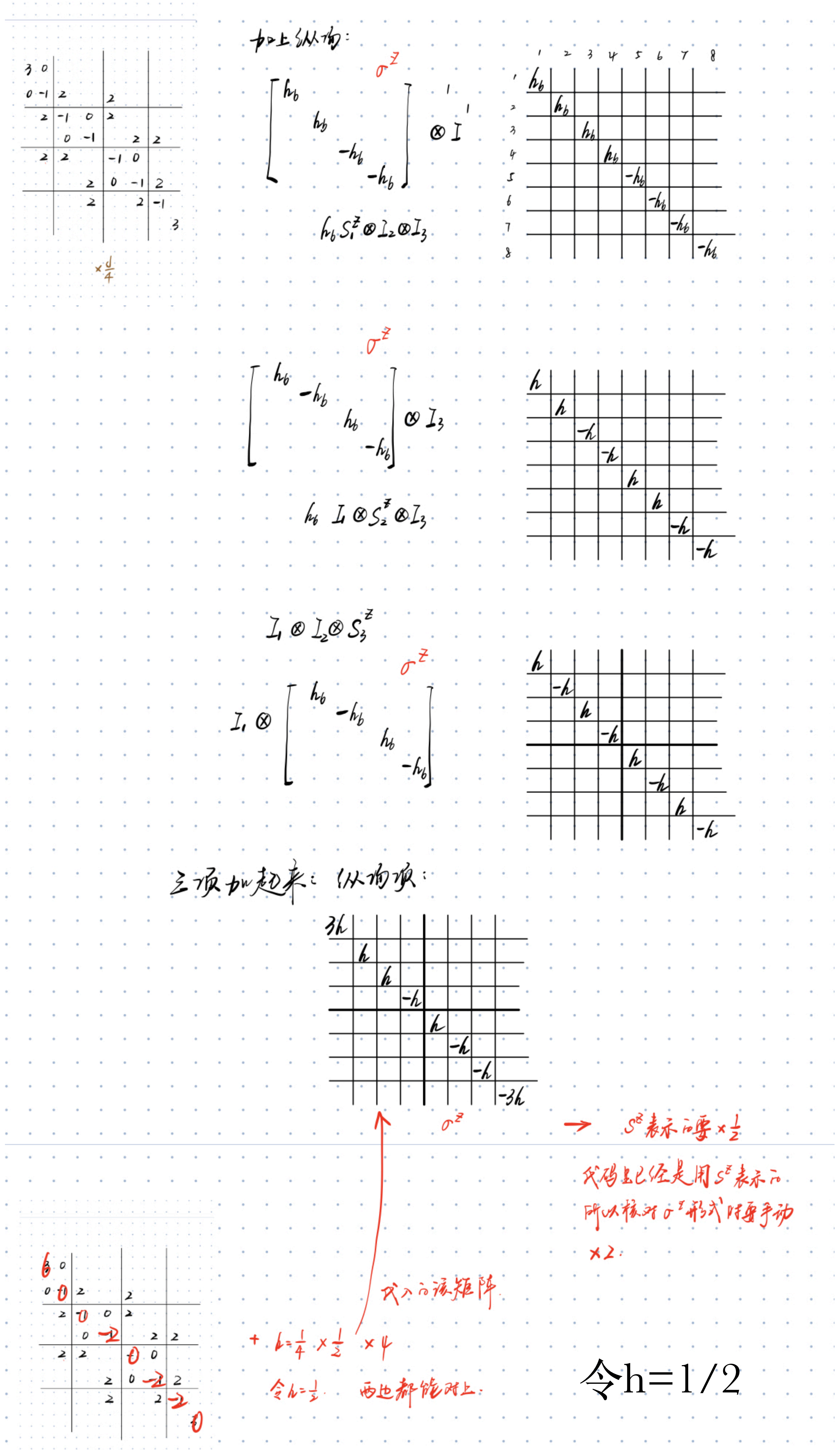
```
H = 4*H;
```

也能对上

H

8x8 double

	1	2	3	4	5	6	7	8
1	6	0	0	0	0	0	0	0
2	0	0	2	0	2	0	0	0
3	0	2	0	0	2	0	0	0
4	0	0	0	-2	0	2	2	0
5	0	2	2	0	0	0	0	0
6	0	0	0	2	0	-2	2	0
7	0	0	0	2	0	2	-2	0
8	0	0	0	0	0	0	0	0



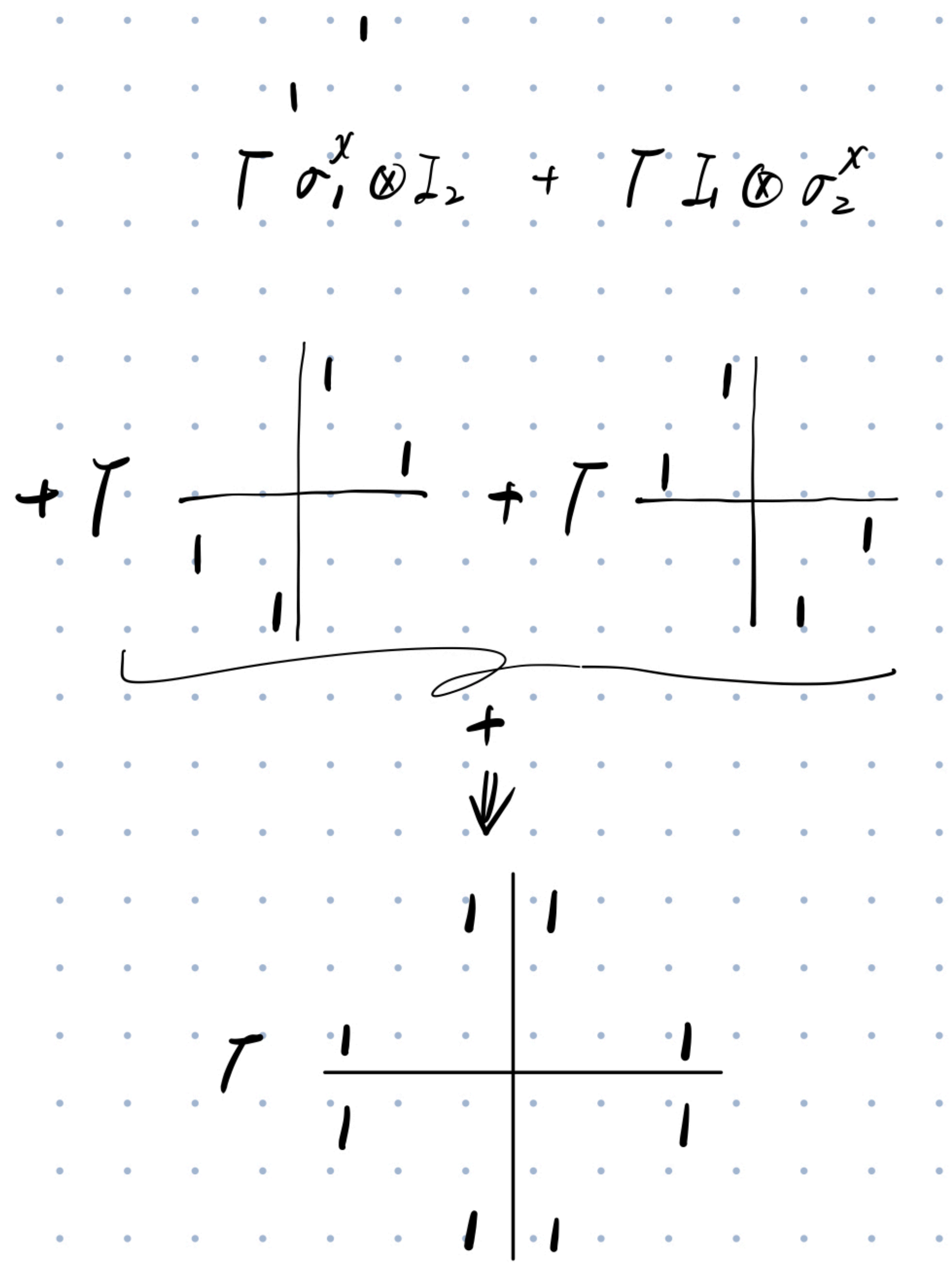
令h=1/2

横场Ising:

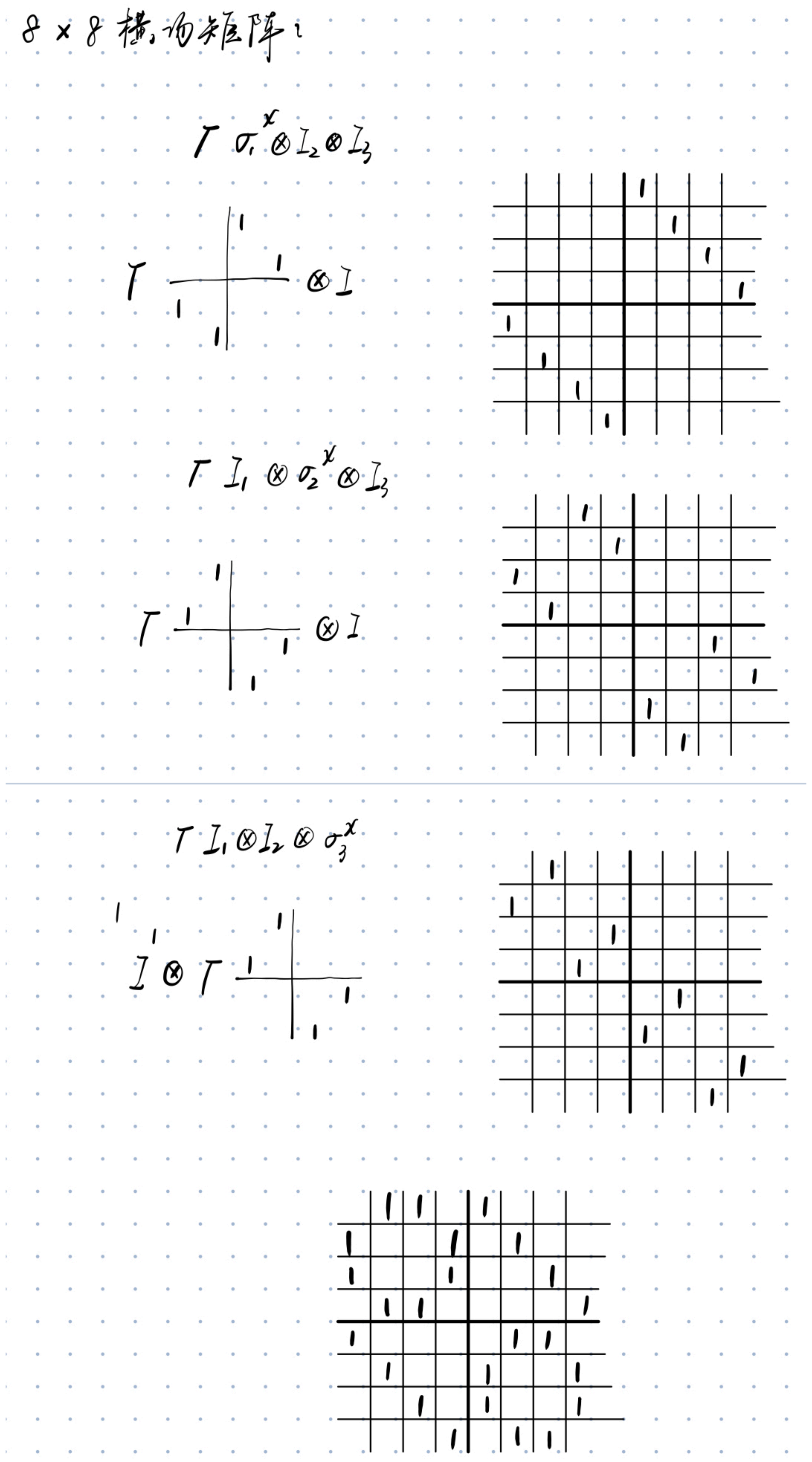
$$H=\sum_{\langle i,j\rangle} J_{i,j}\sigma_i^z\sigma_j^z-\Gamma\sum_i\sigma_i^x \qquad (9)$$

横场的检验： 2/3-spin

```
>> sgamma

sgamma =

     0     1     1     0
     1     0     0     1
     1     0     0     1
     0     1     1     0
```




```
>> sgamma

sgamma =

     0     1     1     0     1     0     0     0
     1     0     0     1     0     1     0     0
     1     0     0     1     0     0     1     0
     0     1     1     0     0     0     0     1
     1     0     0     0     0     1     1     0
     0     1     0     0     1     0     0     1
     0     0     1     0     1     0     0     1
     0     0     0     1     0     1     1     0
```



横场Ising：

$$H = \sum_{\langle i,j \rangle} J_{i,j} \sigma_i^z \sigma_j^z - \Gamma \sum_i \sigma_i^x \tag{9}$$

2-spin

```
H =

     1     1     1     0
     1    -1     0     1
     1     0    -1     1
     0     1     1     1
```

Ising: $J \sigma_1^z \otimes \sigma_2^z$

Ising: 2-spin

$$J \left[\begin{array}{cc|cc} 1 & & & \\ & -1 & & 0 \\ \hline & 0 & -1 & \\ & & & 1 \end{array}\right]$$

$$+ T \left[\begin{array}{cc|cc} & 1 & 1 & \\ 1 & & & 1 \\ \hline 1 & & & 1 \\ & 1 & 1 & \end{array}\right]$$

$J = T = 1$ 时：

$$\left[\begin{array}{cc|cc} 1 & 1 & 1 & 0 \\ 1 & -1 & 0 & 1 \\ \hline 1 & 0 & -1 & 1 \\ 0 & 1 & 1 & 1 \end{array}\right]$$

横场Ising model

$$H=\sum_{\langle i,j\rangle} J_{ij}\sigma_i^z\sigma_j^z-\Gamma\sum_i \sigma_i^x.$$

3-spin

```
H =

     3     1     1     0     1     0     0     0
     1    -1     0     1     0     1     0     0
     1     0    -1     1     0     0     1     0
     0     1     1    -1     0     0     0     1
     1     0     0     0    -1     1     1     0
     0     1     0     0     1    -1     0     1
     0     0     1     0     1     0    -1     1
     0     0     0     1     0     1     1     3
```

8x8矩阵的Ising只是Heisenberg矩阵的对角元（不乘上1/4系数），

此时再把横场加上，矩阵如左表示

4-spin

From https://colab.research.google.com/github/hylu666/hku-physics4150/blob/main/ED/ED_Heisenberg.ipynb#scrollTo=qPJhfmZQgAHr

```
([[1.  , 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.],
  [0., 0., 0.5, 0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0., 0., 0.],
  [0., 0.5, 0., 0., 0.5, 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.],
  [0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.],
  [0., 0., 0.5, 0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0., 0., 0.],
  [0., 0., 0., 0.5, 0., -1., 0.5, 0., 0., 0.5, 0., 0., 0.5, 0., 0., 0.],
  [0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.],
  [0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.5, 0., 0., 0.5, 0.],
  [0., 0.5, 0., 0., 0.5, 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.],
  [0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.],
  [0., 0., 0., 0.5, 0., 0., 0.5, 0., 0., 0.5, -1., 0., 0.5, 0., 0., 0.],
  [0., 0., 0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0., 0.5, 0., 0.],
  [0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0.],
  [0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.5, 0., 0., 0.5, 0.],
  [0., 0., 0., 0., 0., 0., 0., 0.5, 0., 0., 0., 0., 0., 0.5, 0., 0.],
  [0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 1.]])
```

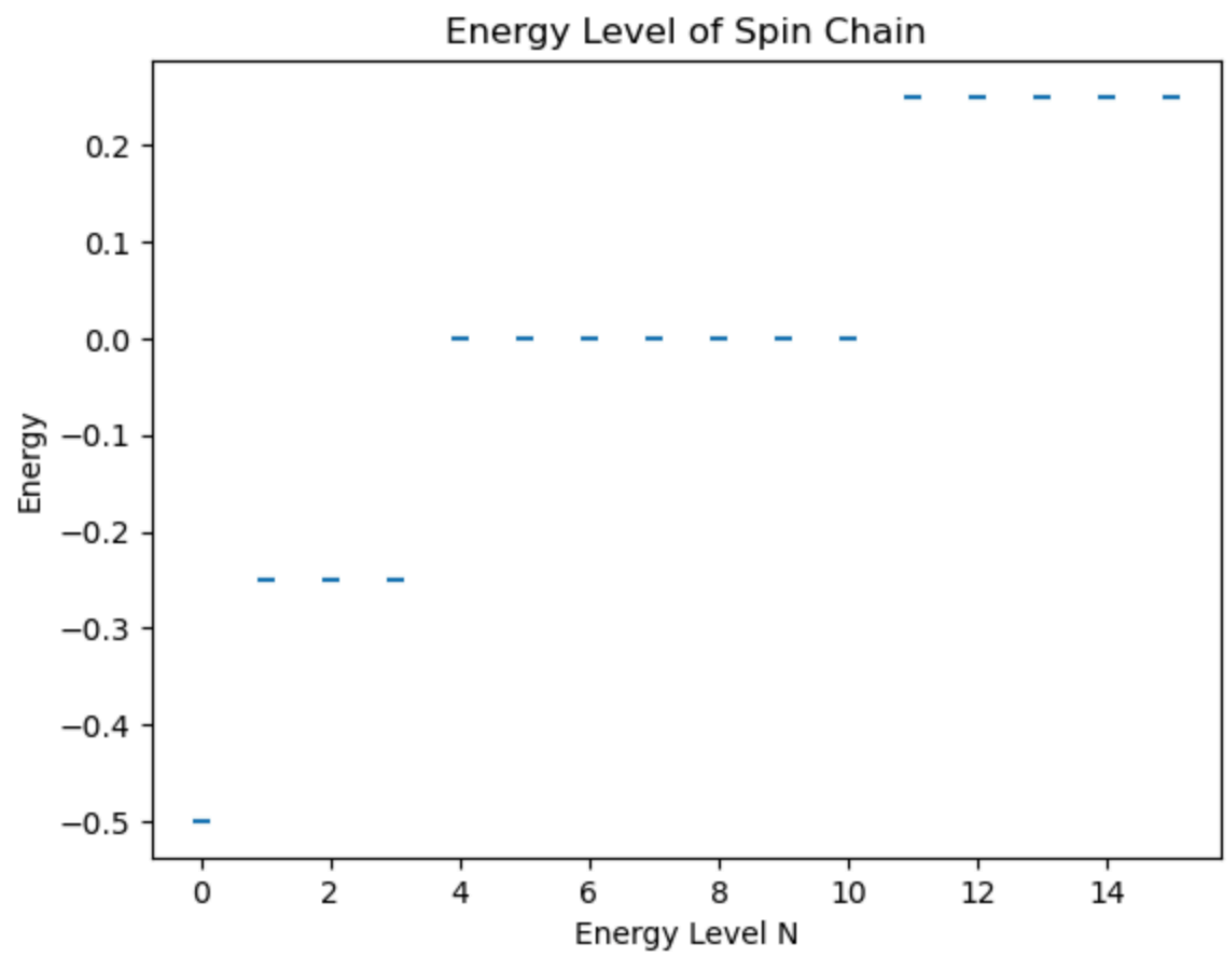
哈密顿量矩阵

Python（来自于别人的ED python）和自己的MATLAB

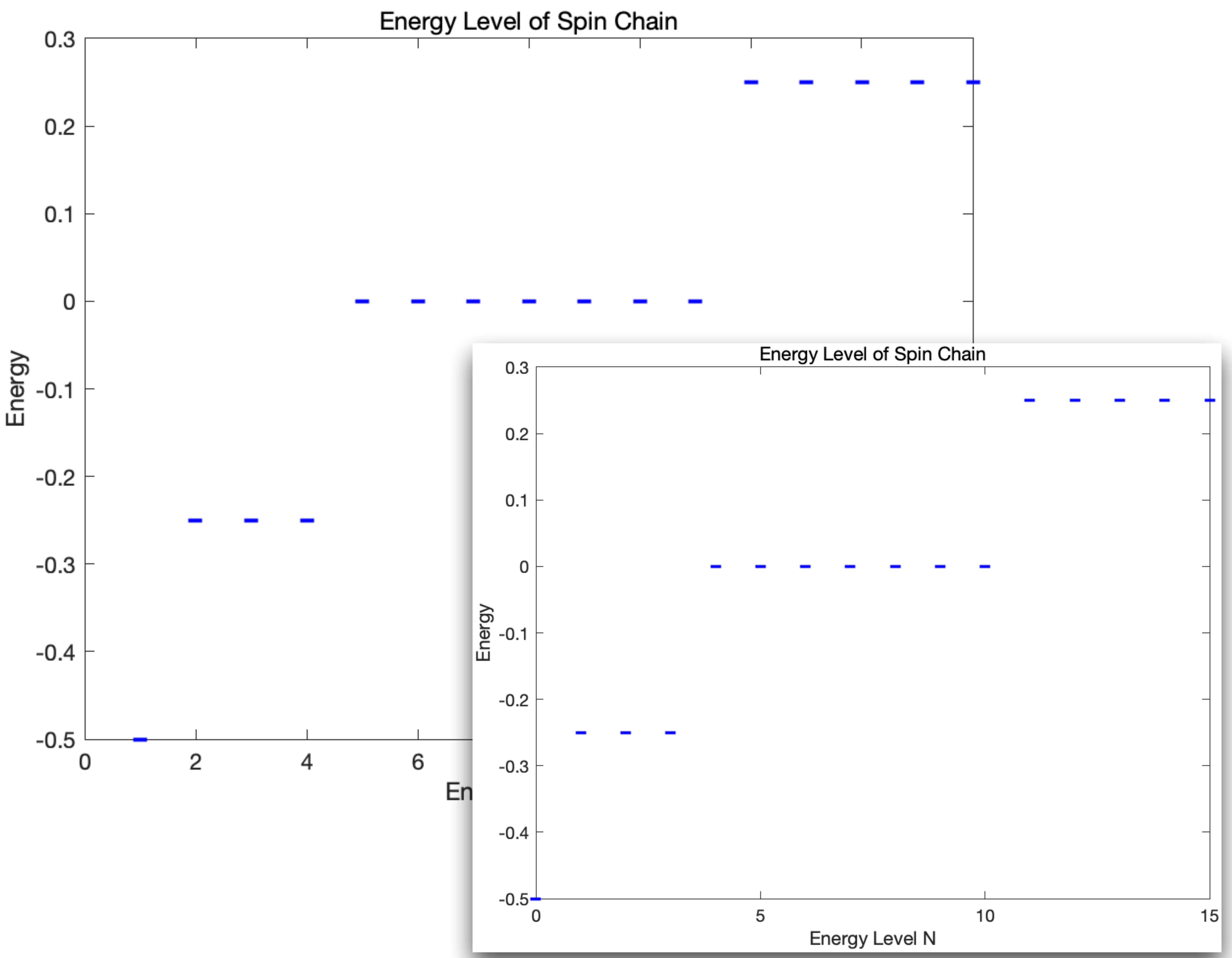
能够对上

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.0000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0.5000	0	0	0	0	0	0.5000	0	0	0	0	0	0	0
3	0	0.5000	0	0	0.5000	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0.5000	0	0	0	0	0.5000	0	0	0	0	0
5	0	0	0.5000	0	0	0	0	0	0.5000	0	0	0	0	0	0	0
6	0	0	0	0.5000	0	-1.0000	0.5000	0	0	0.5000	0	0	0.5000	0	0	0
7	0	0	0	0	0	0.5000	0	0	0	0	0.5000	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0.5000	0	0	0.5000	0
9	0	0.5000	0	0	0.5000	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0.5000	0	0	0	0	0.5000	0	0	0	0	0
11	0	0	0	0.5000	0	0	0.5000	0	0	0.5000	-1.0000	0	0.5000	0	0	0
12	0	0	0	0	0	0	0	0.5000	0	0	0	0	0	0.5000	0	0
13	0	0	0	0	0	0.5000	0	0	0	0	0.5000	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0.5000	0	0	0.5000	0
15	0	0	0	0	0	0	0	0.5000	0	0	0	0	0	0.5000	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0000

能级有些微的不同



plot数据from 上页



调整横坐标取值之后对上了

我怀疑是MATLAB和Python对哈密顿量矩阵的对角化处理会有点不一样

我分别尝试了，将相同的哈密顿量引入MATLAB和python（其中通过csv这个文件导入由MATLAB生成的矩阵）

通过各自的对角化，发现确实存在细微的差别

```
[V,D] = eig(H);
% det(H)
D = diag(D)/L
GS=V(:,1) % gound state
```

D: 16x1 double

	1
1	-0.5000
2	-0.2500
3	-0.2500
4	-0.2500
5	-4.1934e-18
6	-4.1934e-18
7	0
8	0
9	5.7778e-34
10	4.1934e-18
11	4.1934e-18
12	0.2500
13	0.2500
14	0.2500
15	0.2500
16	0.2500

GS: 16x1 double

	1
1	0
2	0
3	0
4	-0.2887
5	0
6	0.5774
7	-0.2887
8	-6.1915e-17
9	0
10	-0.2887
11	0.5774
12	0
13	-0.2887
14	6.1915e-17
15	0
16	0

python

```python
eig_value=np.real(np.linalg.eig(H)[0])# eigen_values
eig_vec=np.real(np.linalg.eig(H)[1])  # eigenstates
```

<u>在数量级~-17的差距有些大</u>

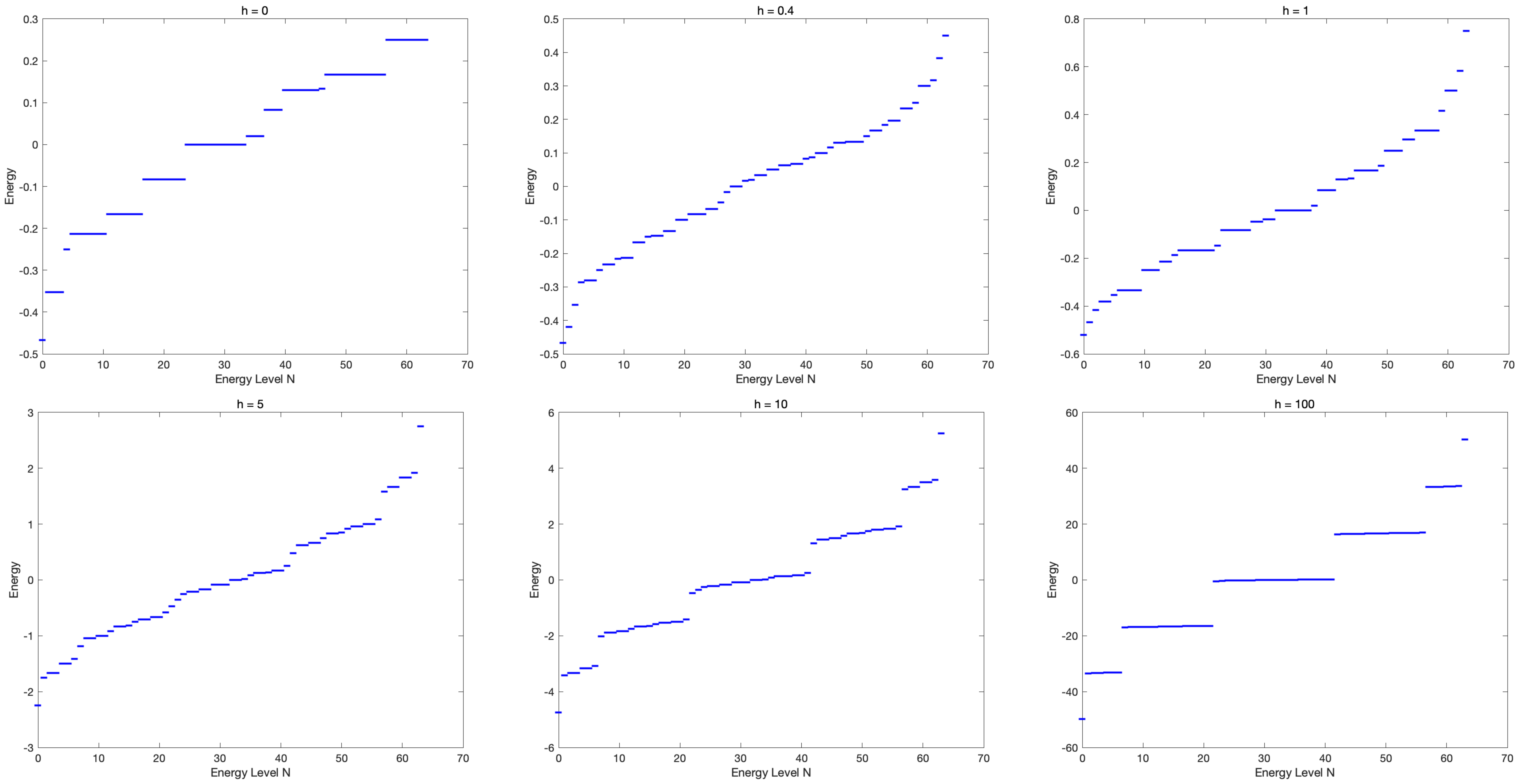
排序后的本征值

```
[-5.00000000e-01 -2.50000000e-01 -2.50000000e-01 -2.50000000e-01
 -3.82580930e-17 -1.41786105e-17 -1.13040275e-33 -5.53653701e-34
  3.16194328e-33  1.35833475e-17  2.42420365e-17  2.50000000e-01
  2.50000000e-01  2.50000000e-01  2.50000000e-01  2.50000000e-01]
```

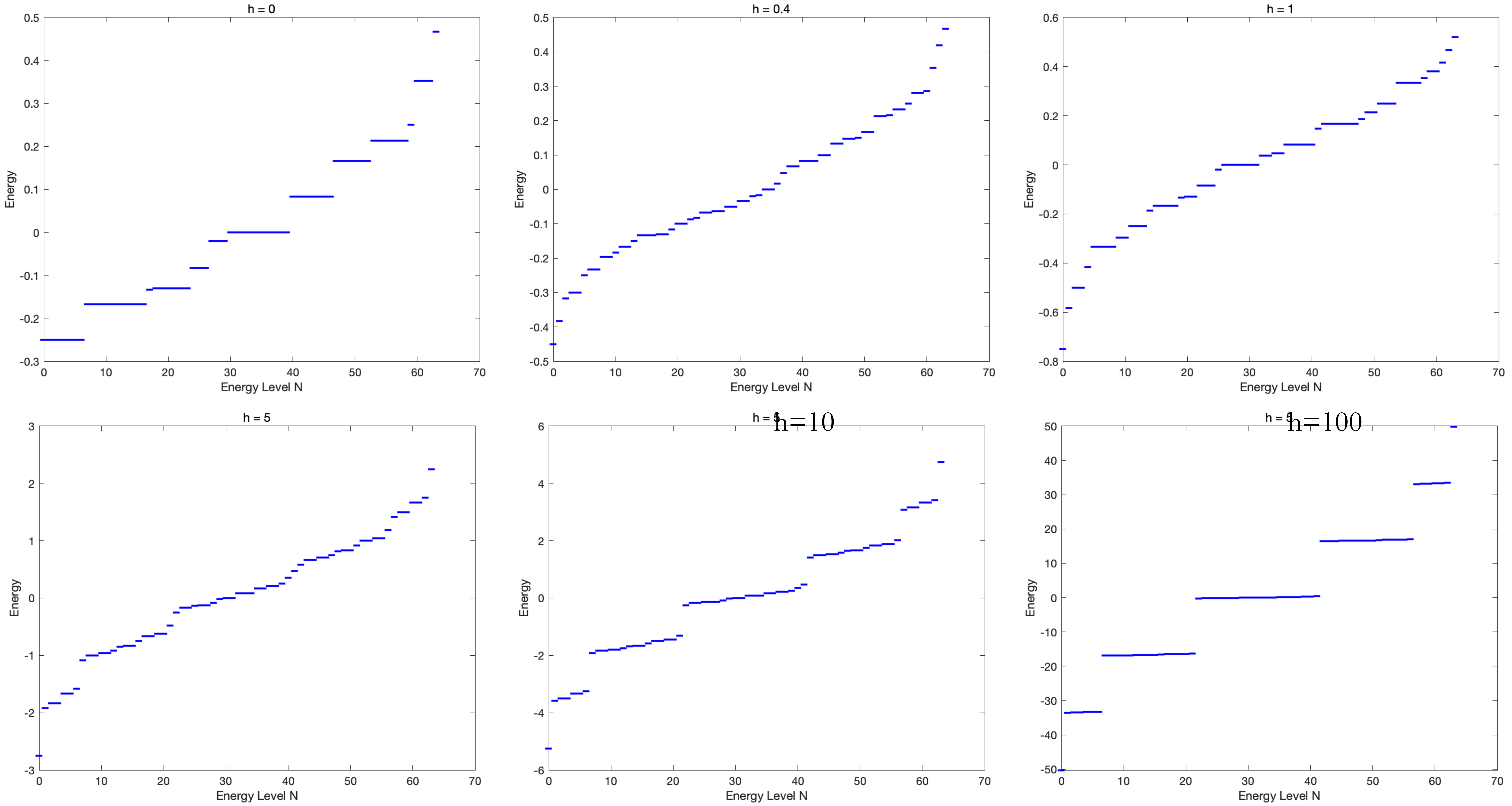
基态波函数

```
[ 0.00000000e+00  5.54163012e-17  1.09226604e-17  2.88675135e-01
 -1.65708221e-16 -5.77350269e-01  2.88675135e-01 -3.20493781e-17
  1.09226604e-17  2.88675135e-01 -5.77350269e-01  4.95678897e-33
  2.88675135e-01  3.20493781e-17  5.98276725e-33  0.00000000e+00]
```

加上纵场的能级　　6-spin　　AFM +/- h



FM +/- h



绘制的代码:

```
[V,D] = eig(H);
% det(H)
D = diag(D)/L
GS=V(:,1) % gound state

GSE = min(D)

% Plotting Energy Level of Spin Chain
energy_level = D; % Assuming the division by 4 is required for the plot
figure;
plot(0:length(energy_level)-1, energy_level, '_','Color', 'blue', 'LineWidth', 2);
xlabel('Energy Level N');
ylabel('Energy');
title('h = 0');
```