

# 発光励起スペクトルを用いた T型量子細線中の励起子励起状態の観測

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## アウトライン

- T型量子細線について
- 実験手法について
- 理論計算について
- 比較・議論



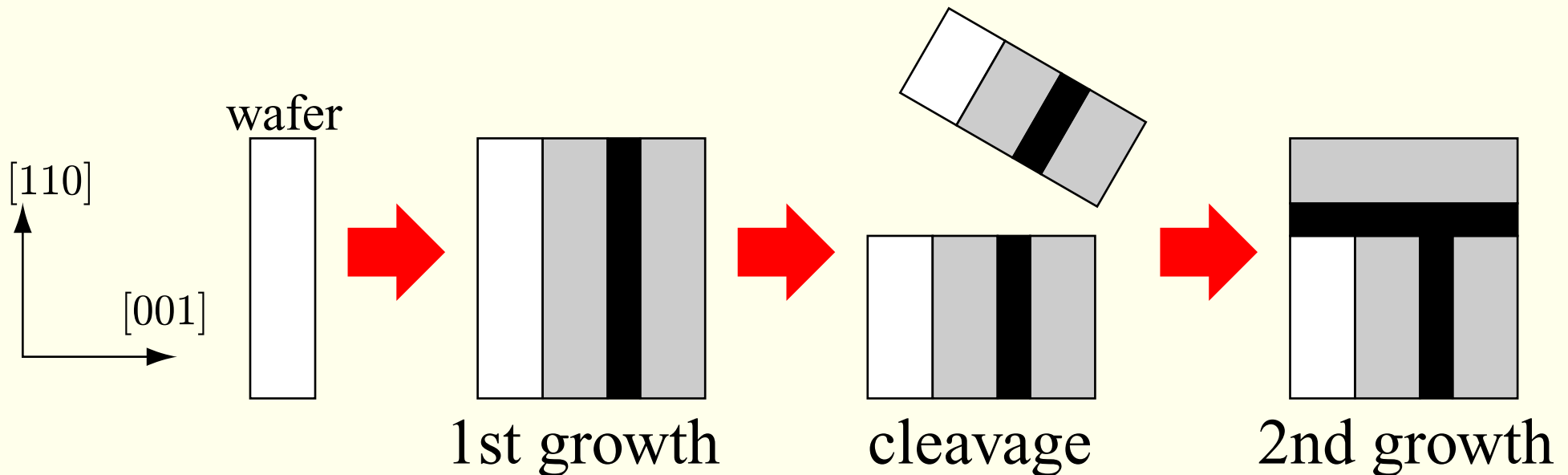
# # T型量子細線とは？

## 量子細線 (quantum wire)

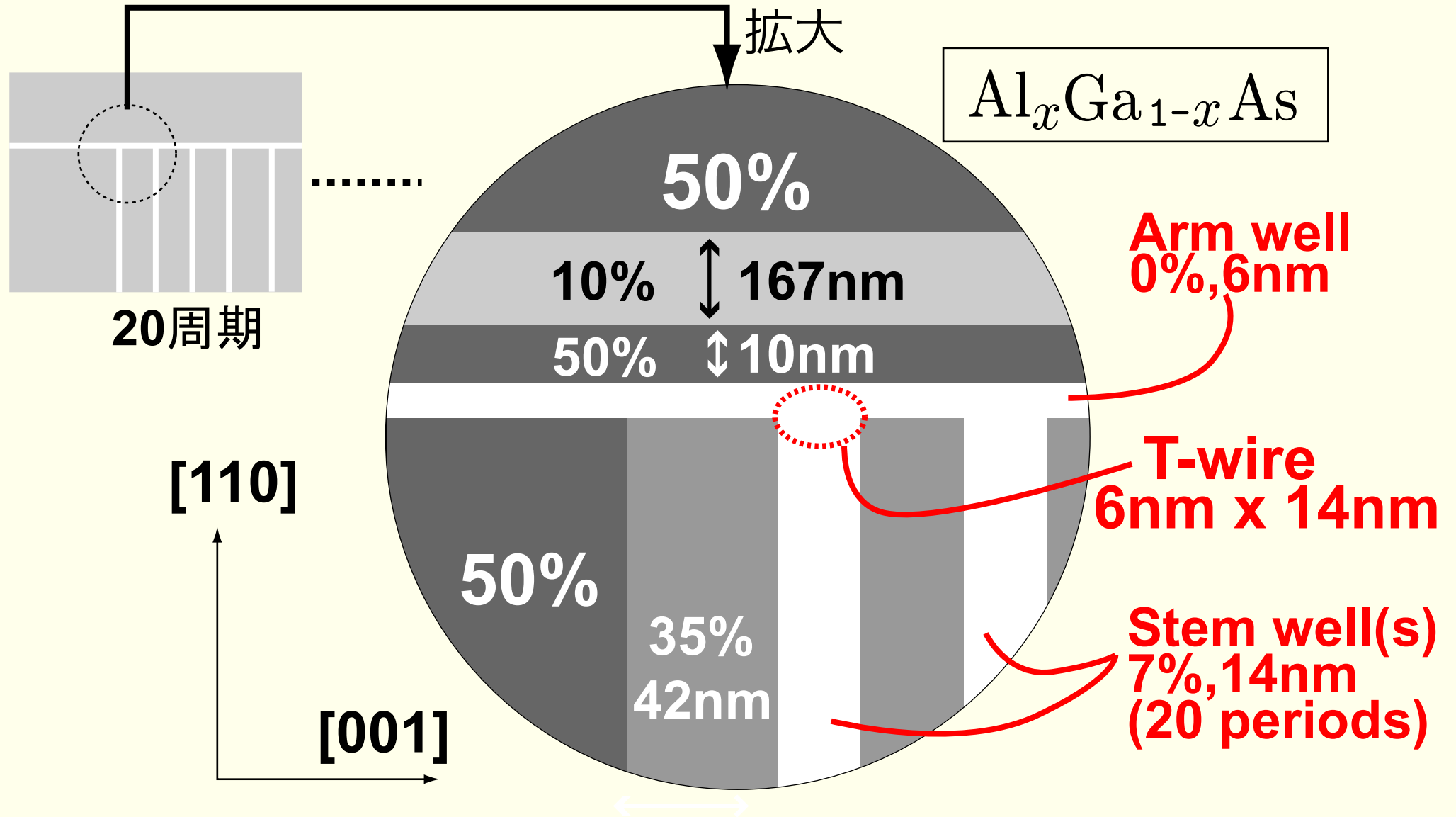
- 人工的な擬1次元系
- デバイス応用及び1次元系の基礎物性への理解が目的

### T型

- 二段階のMBE成長で、量子井戸をT型に交差  
→ 井戸の交線は量子細線として振る舞う

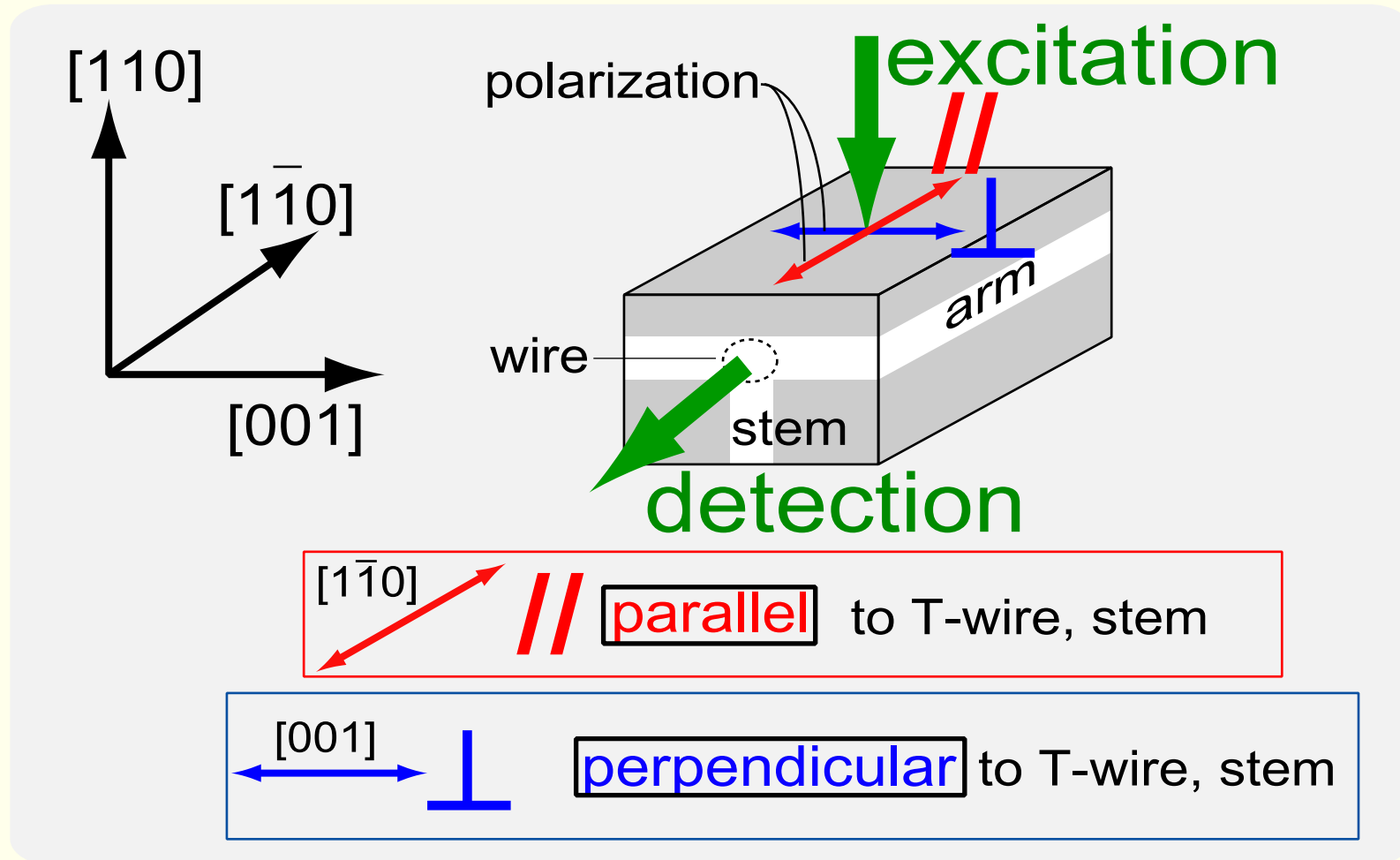


# # 試料の詳細



Arm well, Stem well の交線に 6nm x 14nm の量子細線が形成

# # 実験にまつわる情報

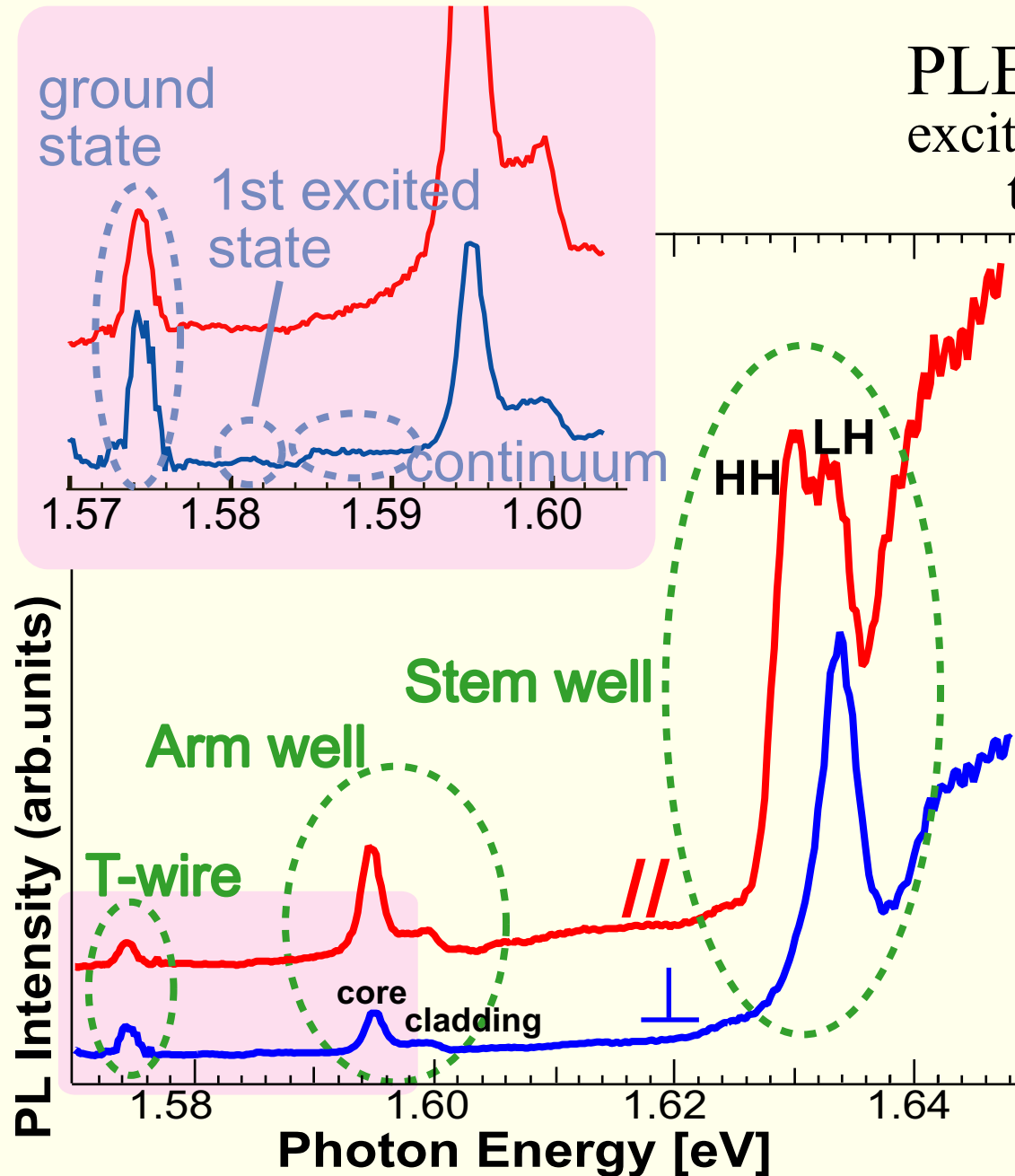


excited at:  $6.7[\mu\text{W}]$

4.9 K (in cryostat)

by: tunable cw-TiS laser (resolution: 0.3 [meV])

# # 前回 (日本物理学会 '02 秋季大会) の報告



PLE spectrum of T-wire sample  
excitation power:  $6.7[\mu\text{W}]$   
temperature: 3.7 K

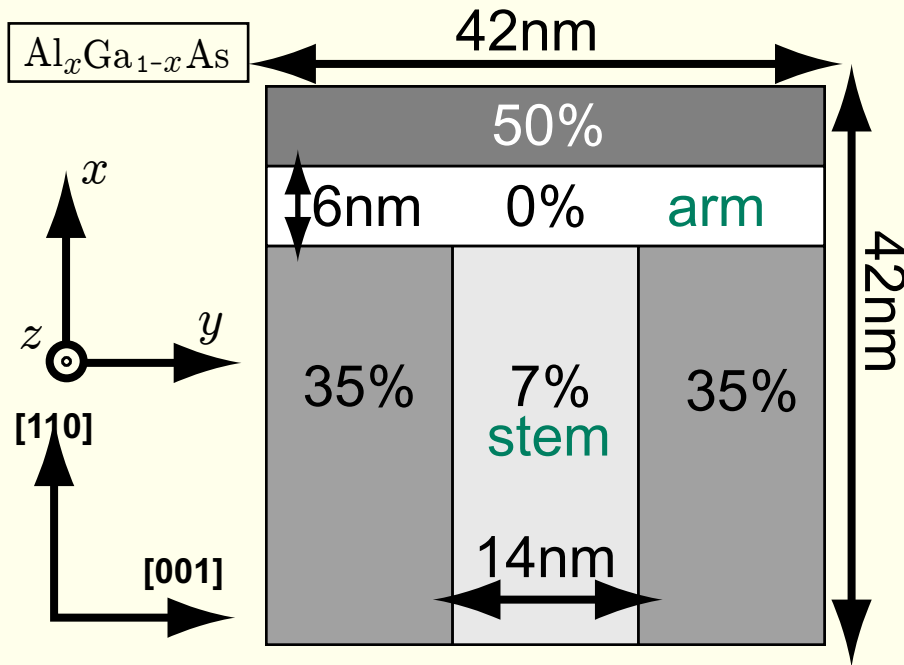
- 精度良い偏光依存PLEを測定
- 連続状態の観測に成功。

Coulomb相互作用によって吸収が抑えられるという理論予測と一致  
Ogawa and Takagahara  
PRB **43** 14325 (1991)

- 第1励起状態の観測に成功。

Szymanska *et al.*  
PRB **63** 205317 (2001)

# # Szymanskaらの計算



$$\mathcal{H} = \mathcal{H}_e + \mathcal{H}_h + q$$

電子・重い正孔の1粒子ハミルトニアン  
(有効質量近似)

電子・正孔間のCoulombポテンシャル

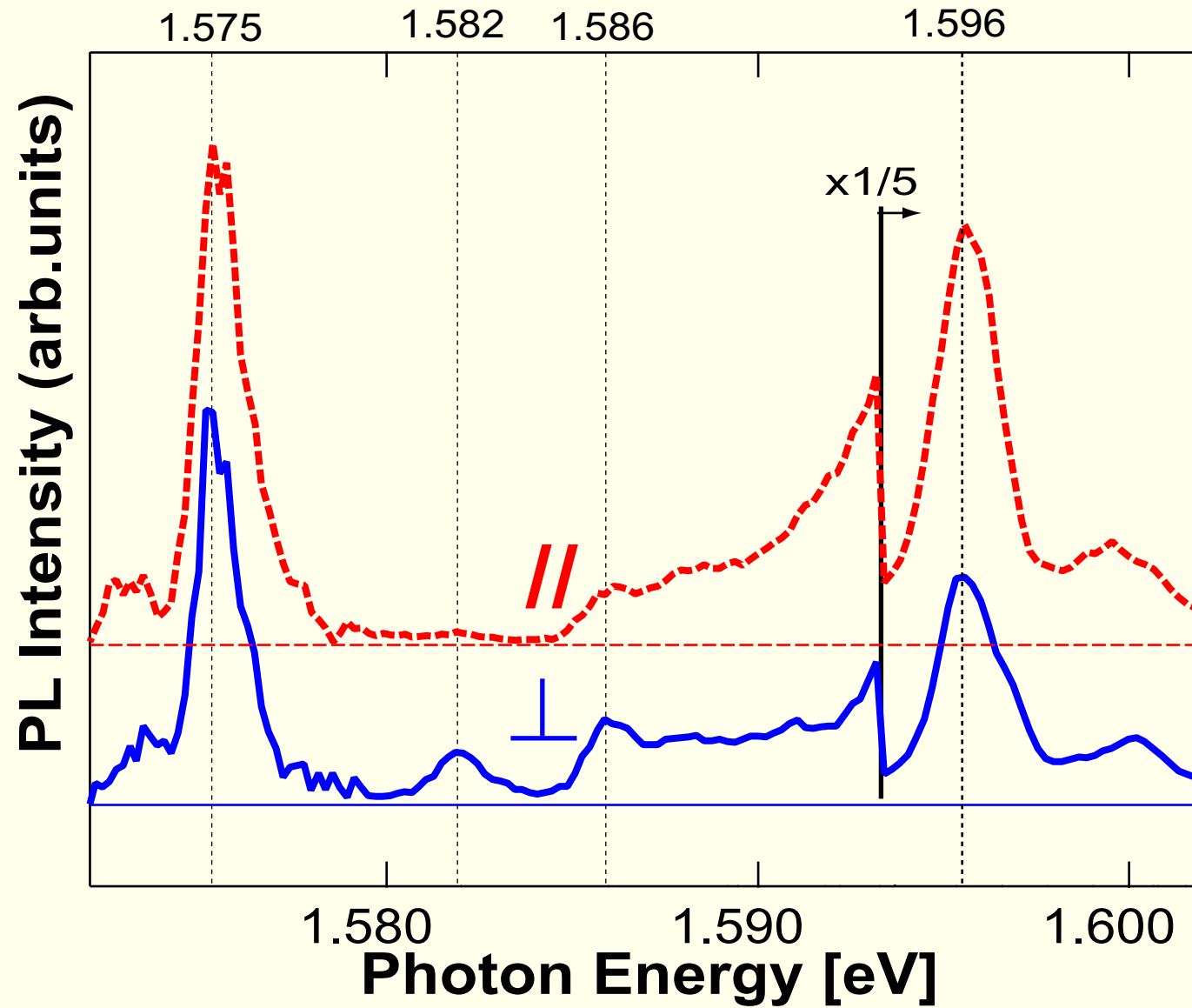
$$\sum_{i,j,k} c_{i,j,k} \underbrace{\sin\left(\frac{z\pi}{L_z}k - \frac{\pi}{2}k\right)}_{z \text{ 方向の平面波}} \underbrace{\chi_i^e(x_e, y_e)}_{\text{電子}} \underbrace{\chi_j^h(x_h, y_h)}_{\text{正孔}} \text{ なる基底で対角化}$$

→  $\Psi_n(x_e, y_e, x_h, y_h, z)$  を得る

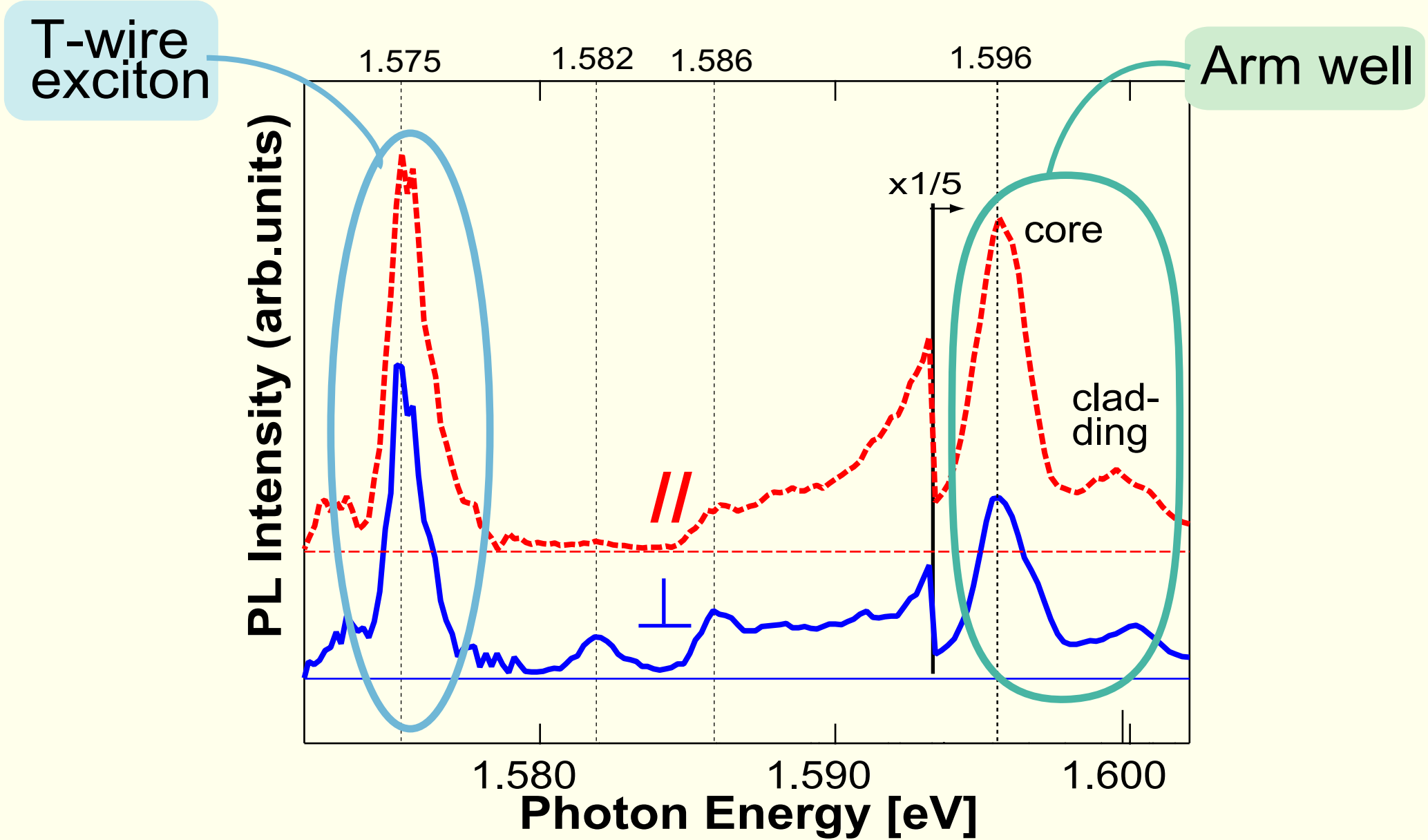
$n$ : 準位の番号、  
 $z = z_e - z_h$   
は相対座標

※ 1D連続状態、2D励起子基底状態のエネルギーも併せて導出

# # 実験結果と計算結果

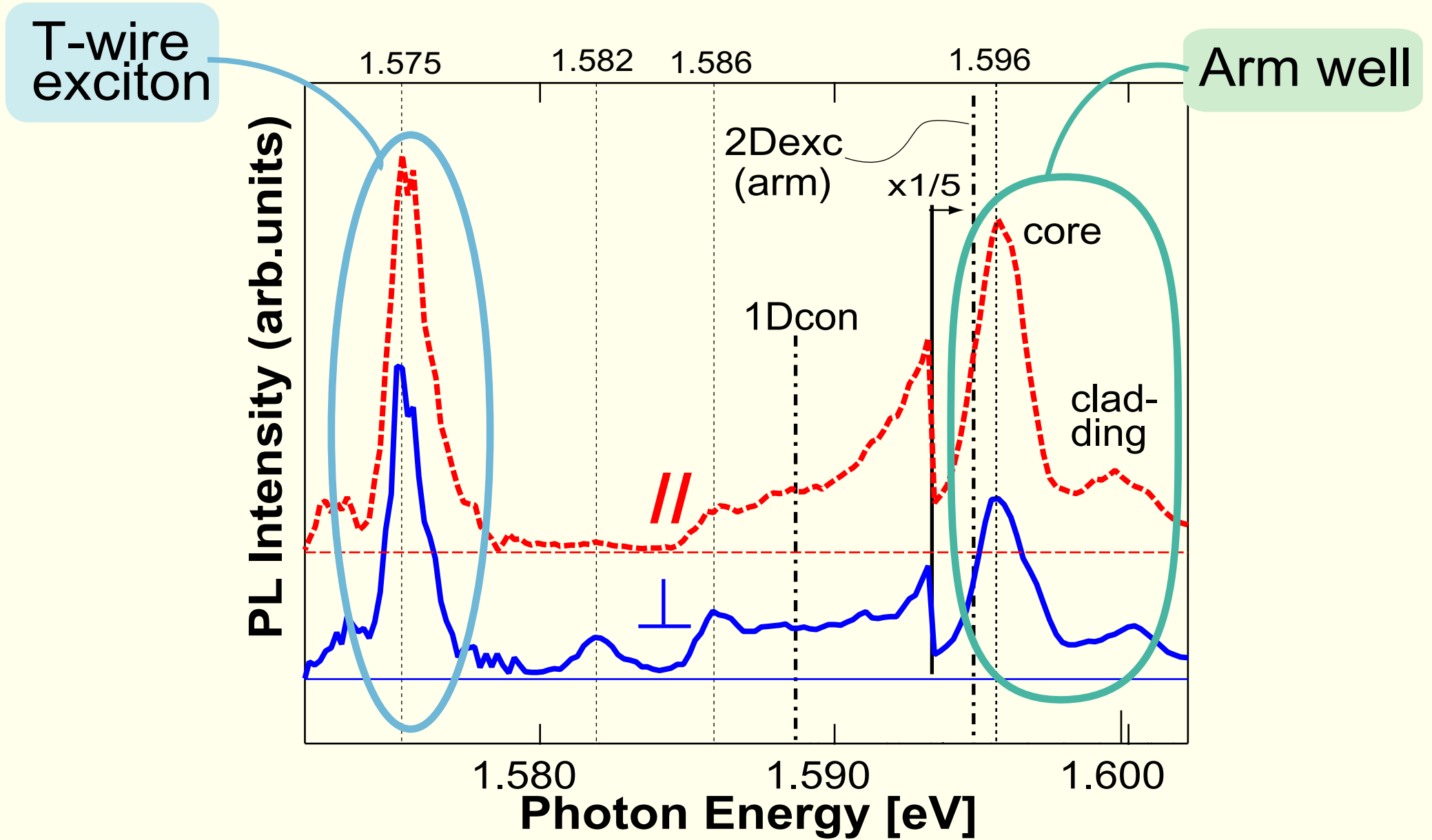


# # 実験結果と計算結果

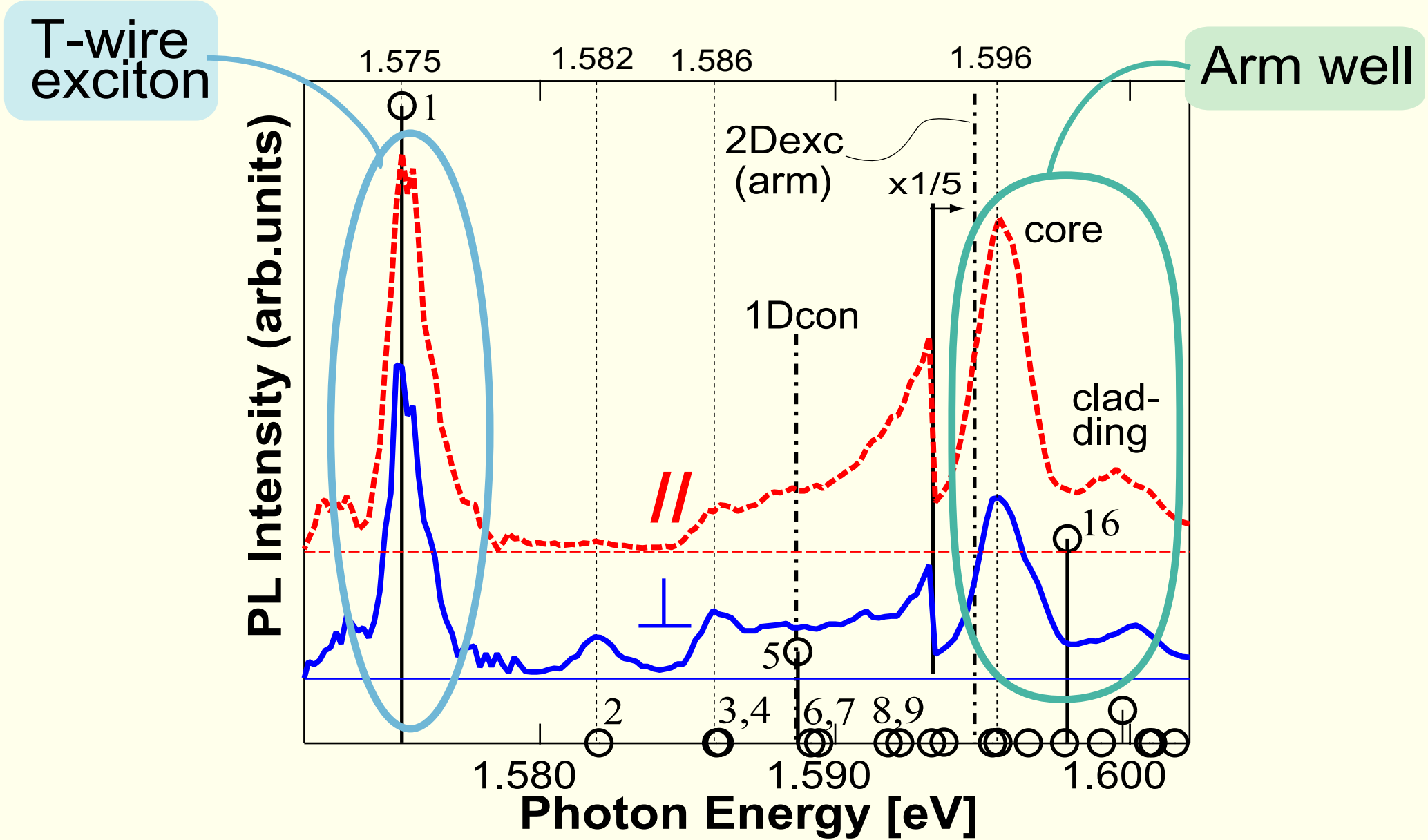




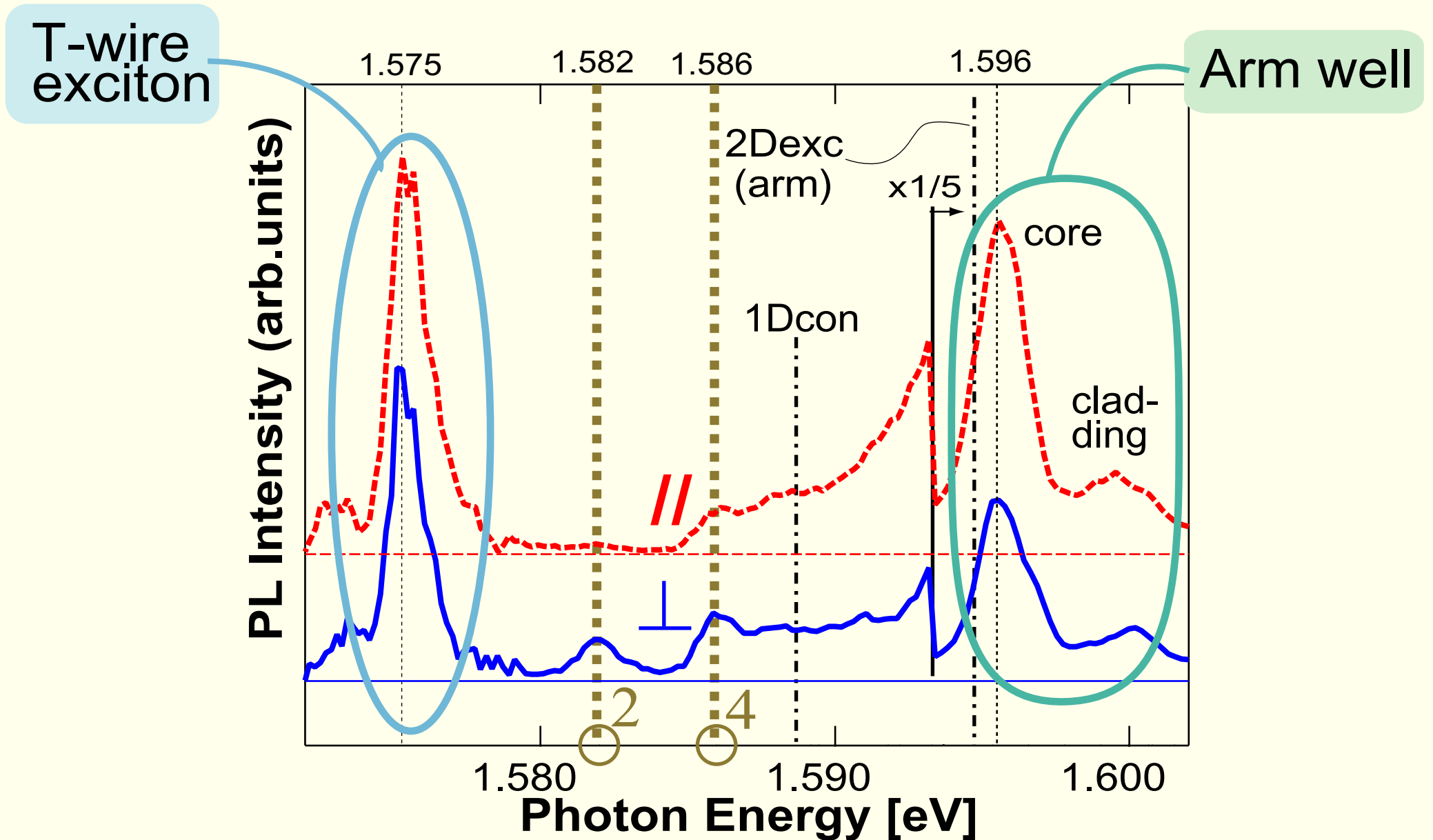
# # 実験結果と計算結果



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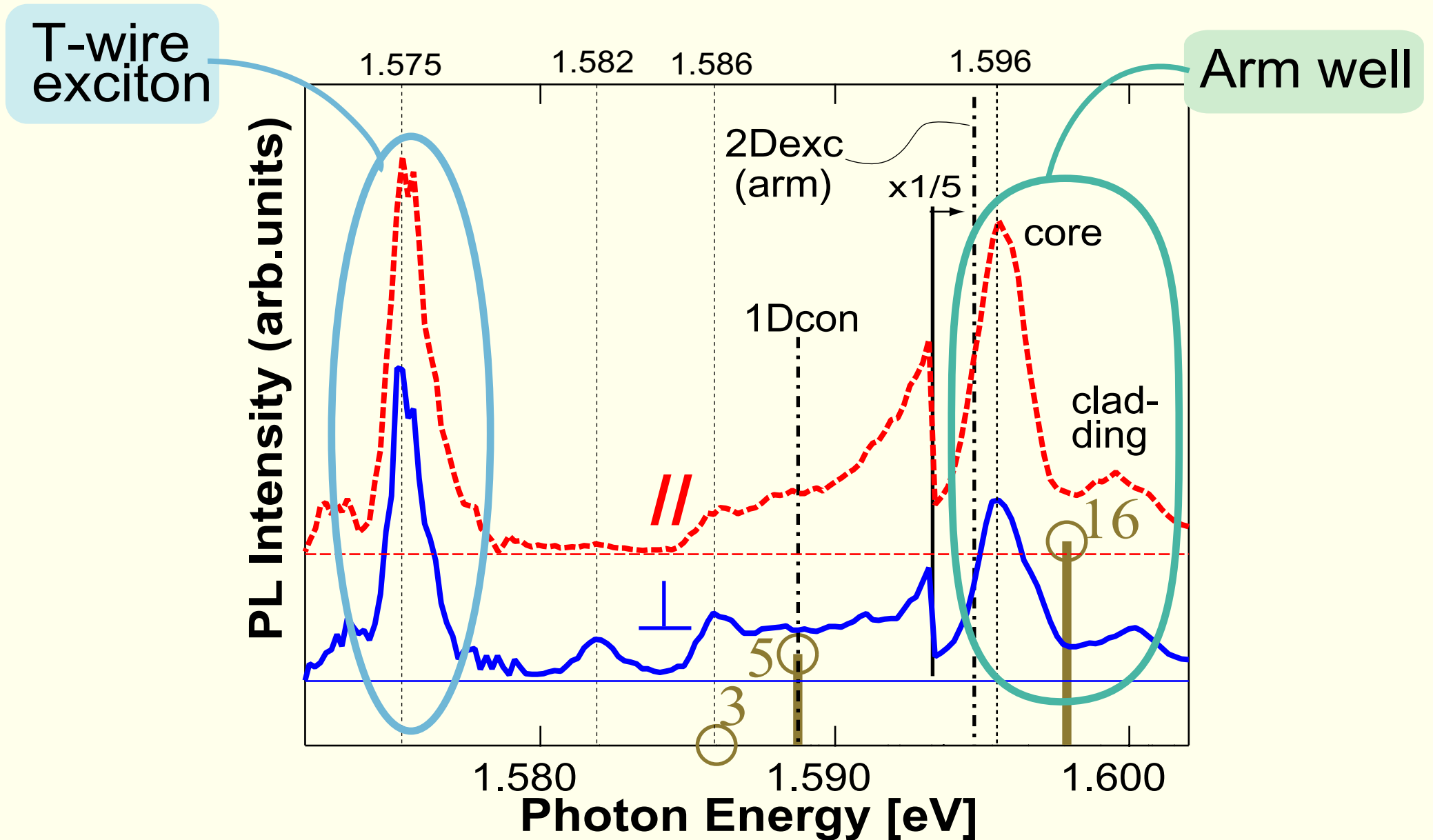


# # 実験結果と計算結果



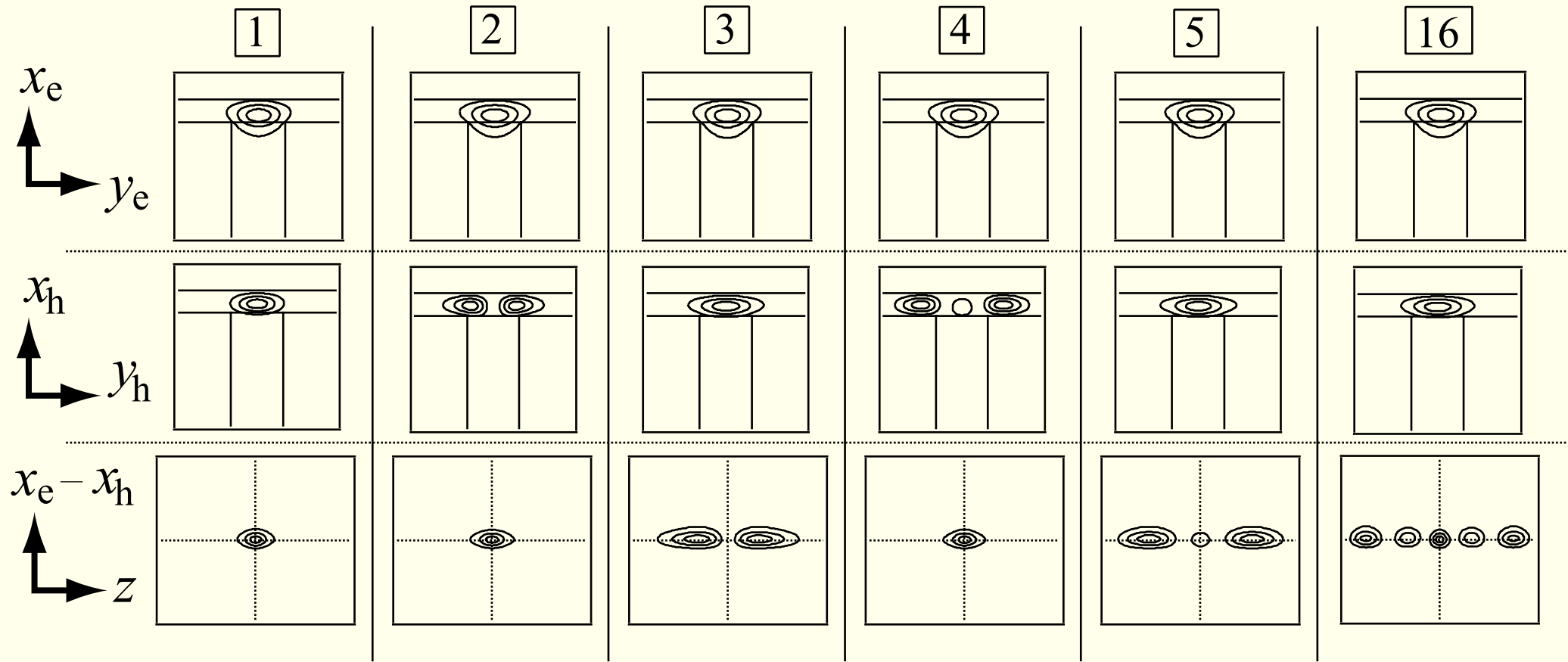
「正孔の励起状態」を含む「励起子の基底状態」

# # 実験結果と計算結果

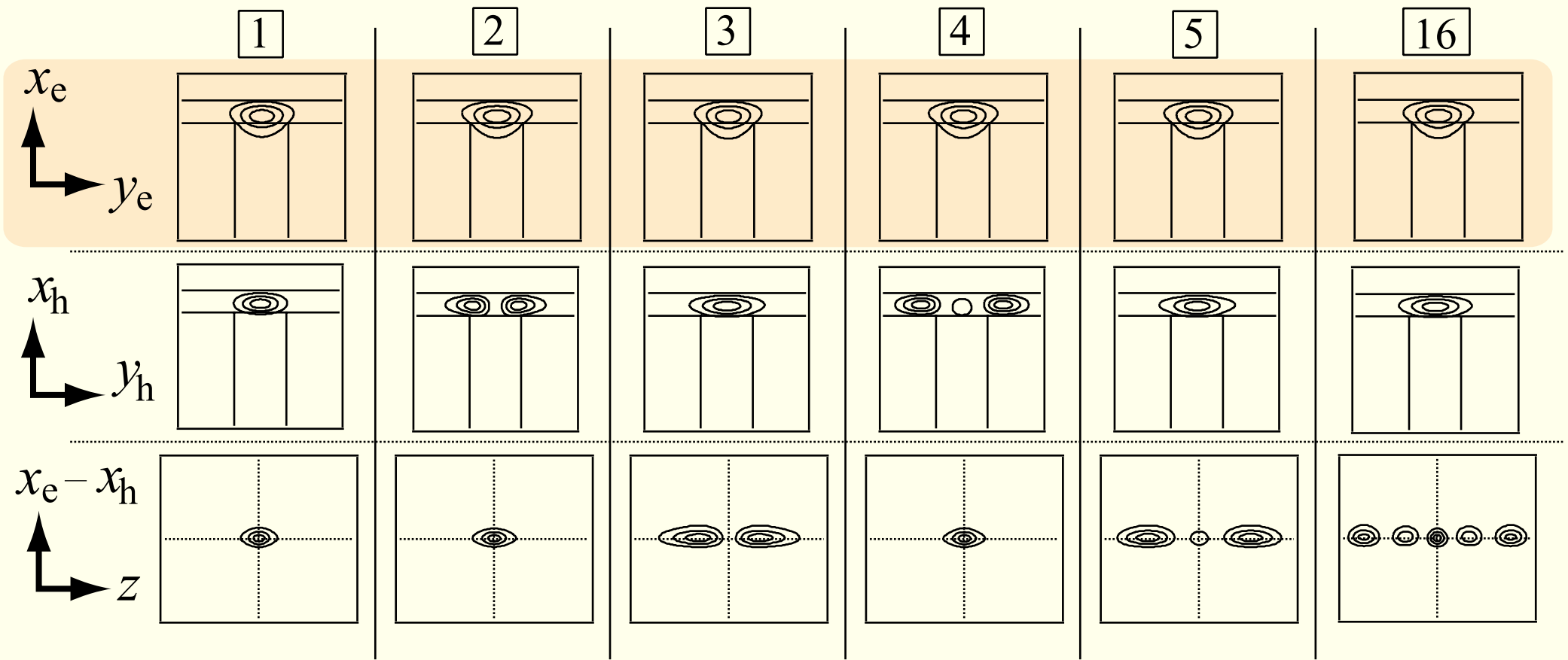


「正孔の基底状態」を含む「励起子の励起状態」

# # 波動関数の詳細

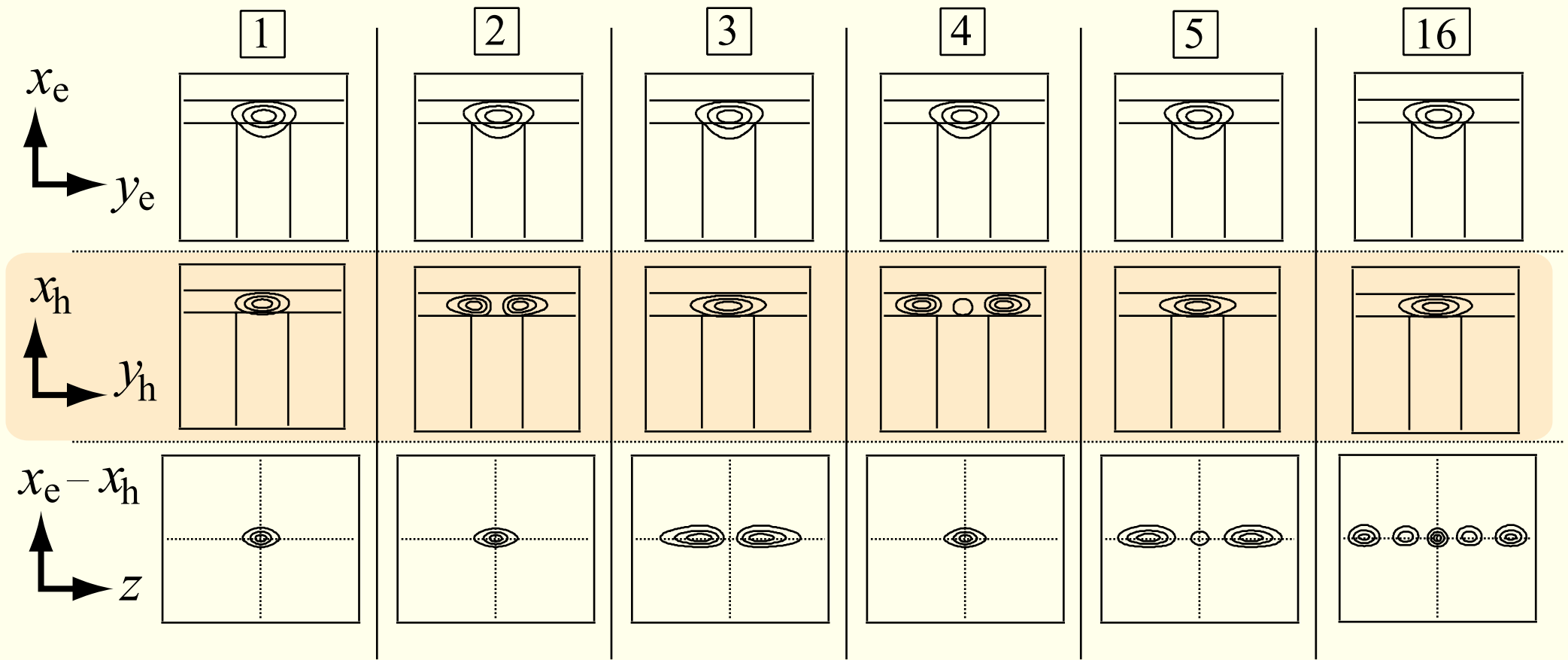


# # 波動関数の詳細



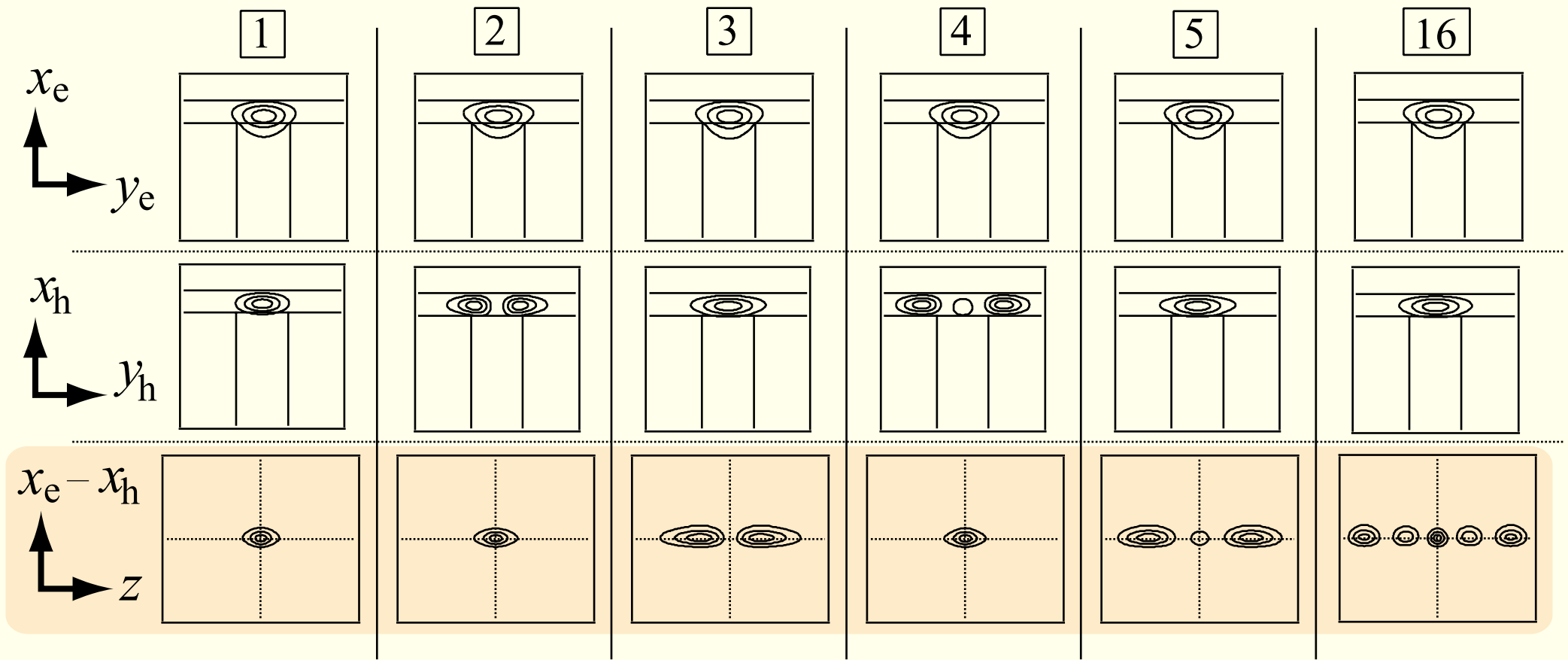
電子は基底状態にある (20番目の準位まで)

# # 波動関数の詳細



正孔の状態は様々に変わる

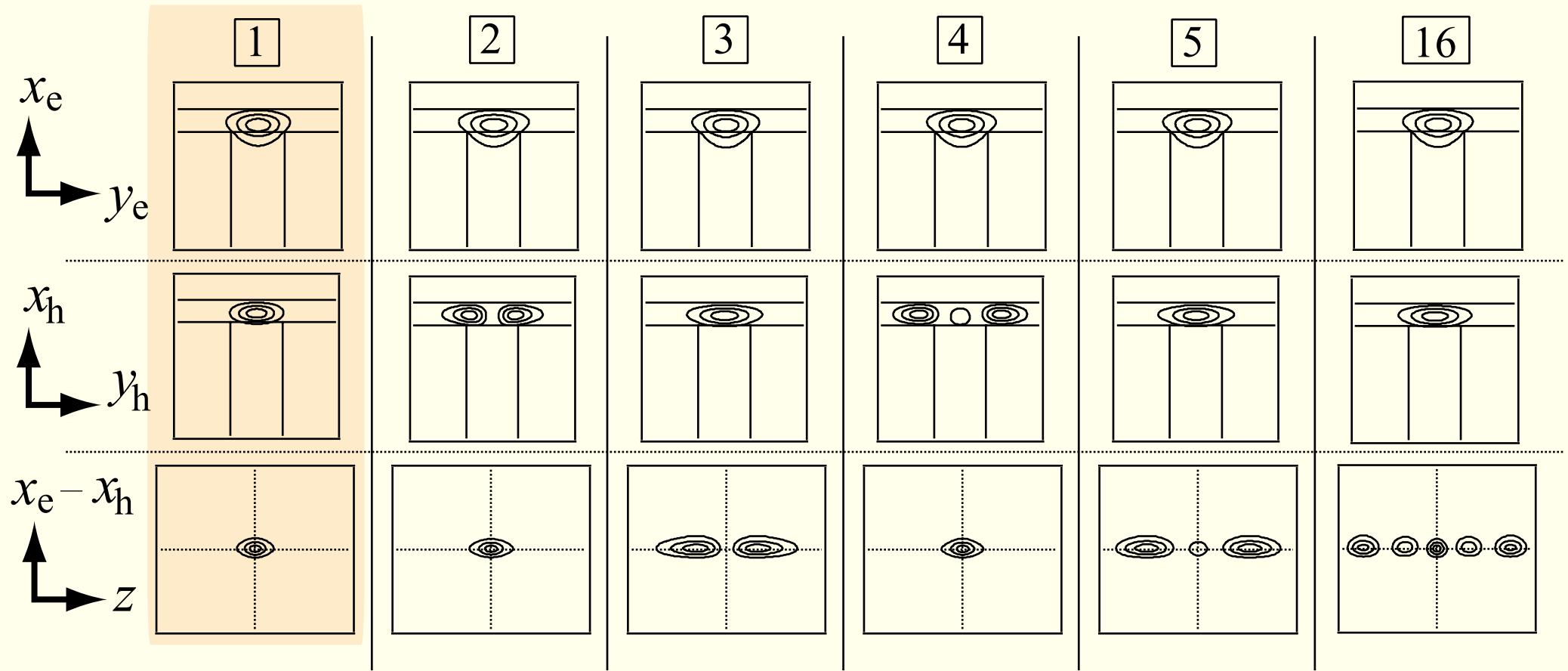
# # 波動関数の詳細



励起子の状態も様々に変わる

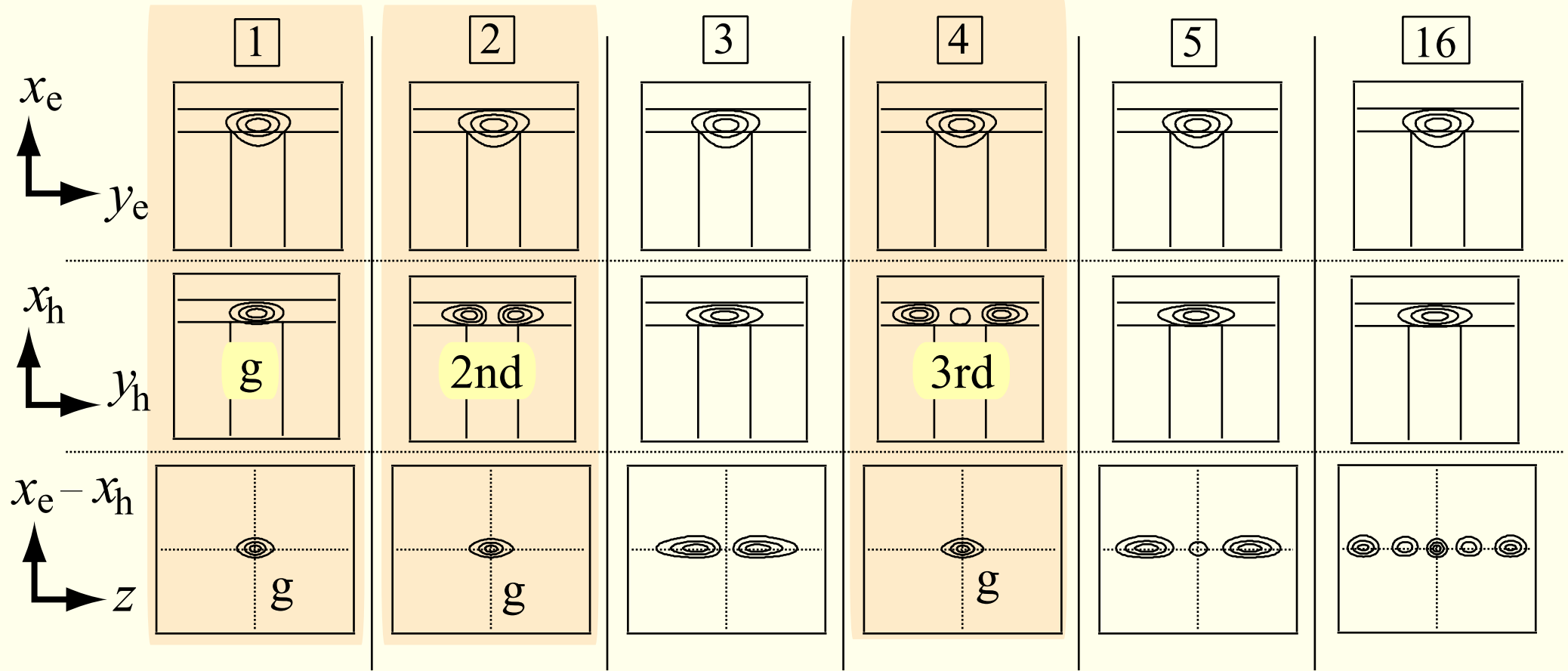


# # 波動関数の詳細



基底状態で励起子や正孔は良く閉じこもる

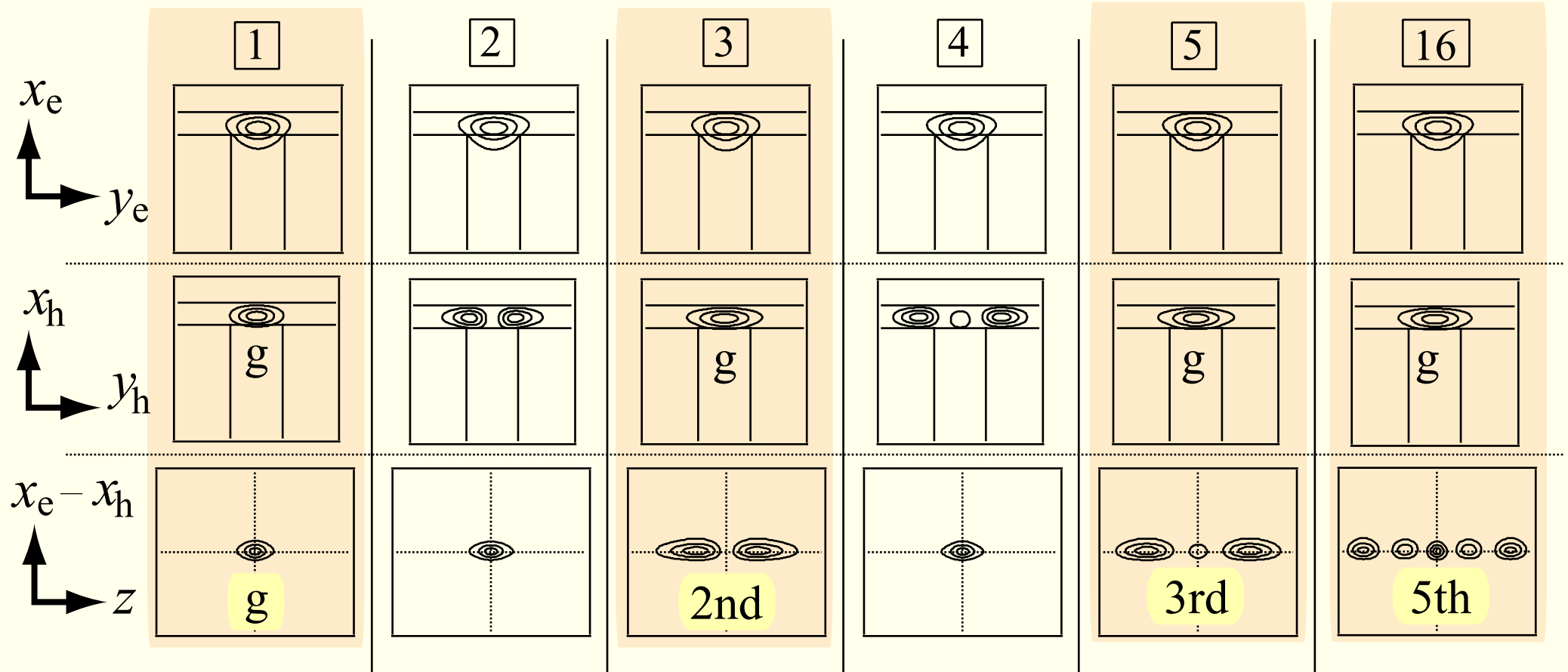
# # 波動関数の詳細



「正孔の励起状態」を含む「励起子の基底状態」

正孔は端のポテンシャルを感じる  
→エネルギーのズレ小（正孔の質量は重い）

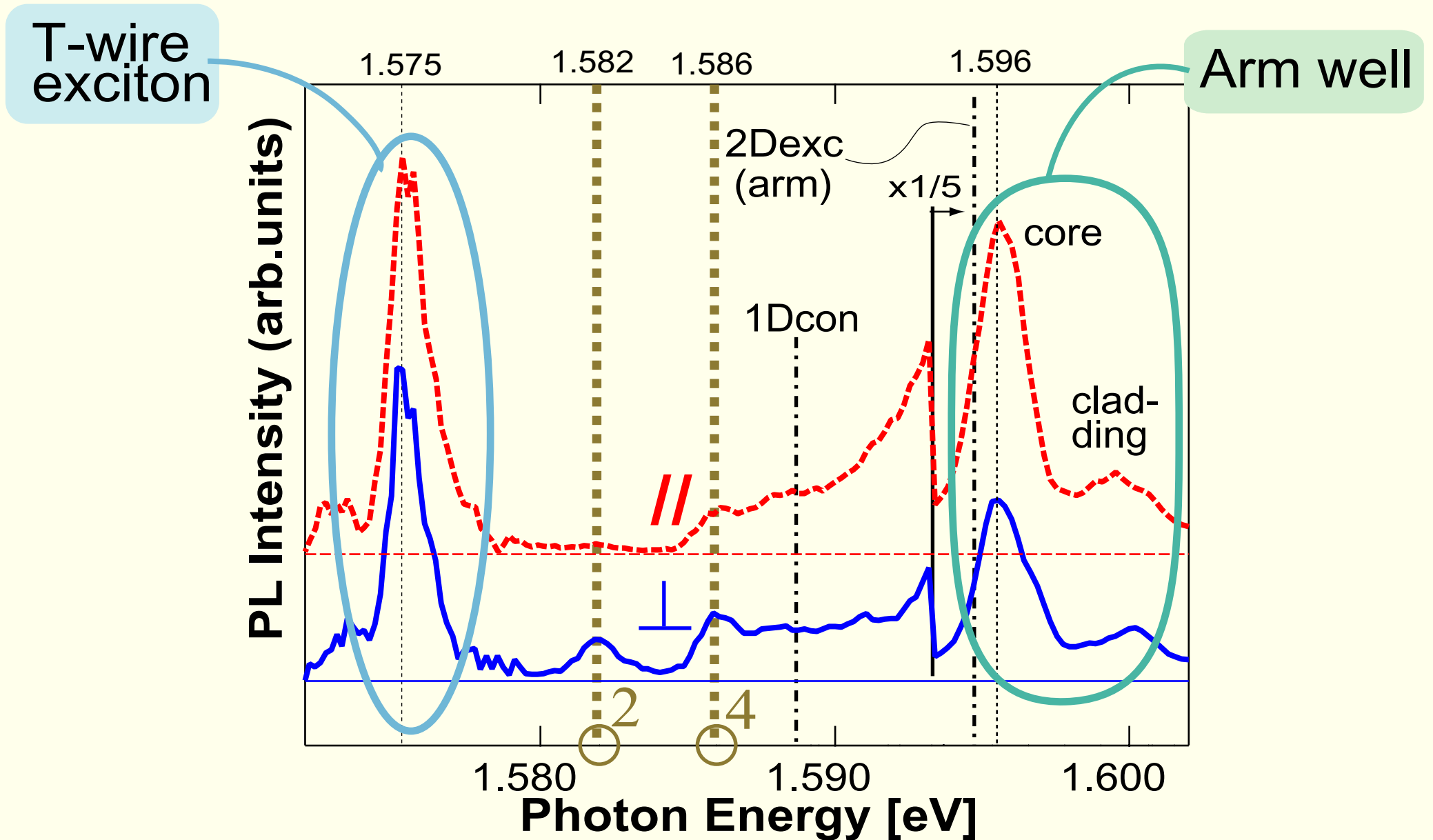
# # 波動関数の詳細



「正孔の基底状態」を含む「励起子の励起状態」

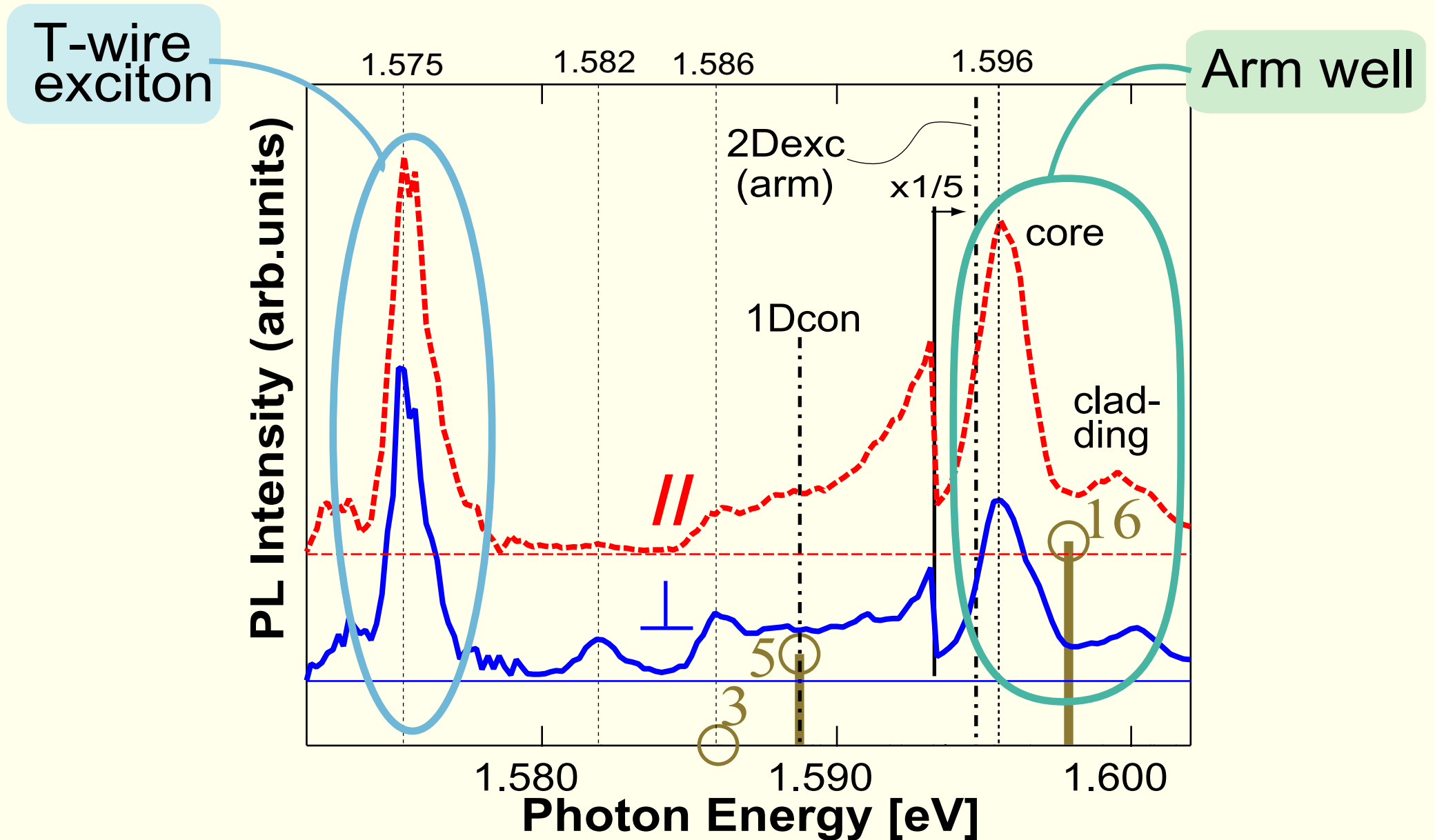
励起子は端のポテンシャルを感じる  
→ エネルギーのズレ大 (電子の質量は軽い)

# # 実験結果と計算結果



「正孔の励起状態」を含む「励起子の基底状態」

# # 実験結果と計算結果



「正孔の基底状態」を含む「励起子の励起状態」

# # まとめ

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## 結論

- ・ T型量子細線の偏光依存PLEを精度良く観測した
- ・ 理論計算との比較と併せ、各ピークの起源を明らかにした

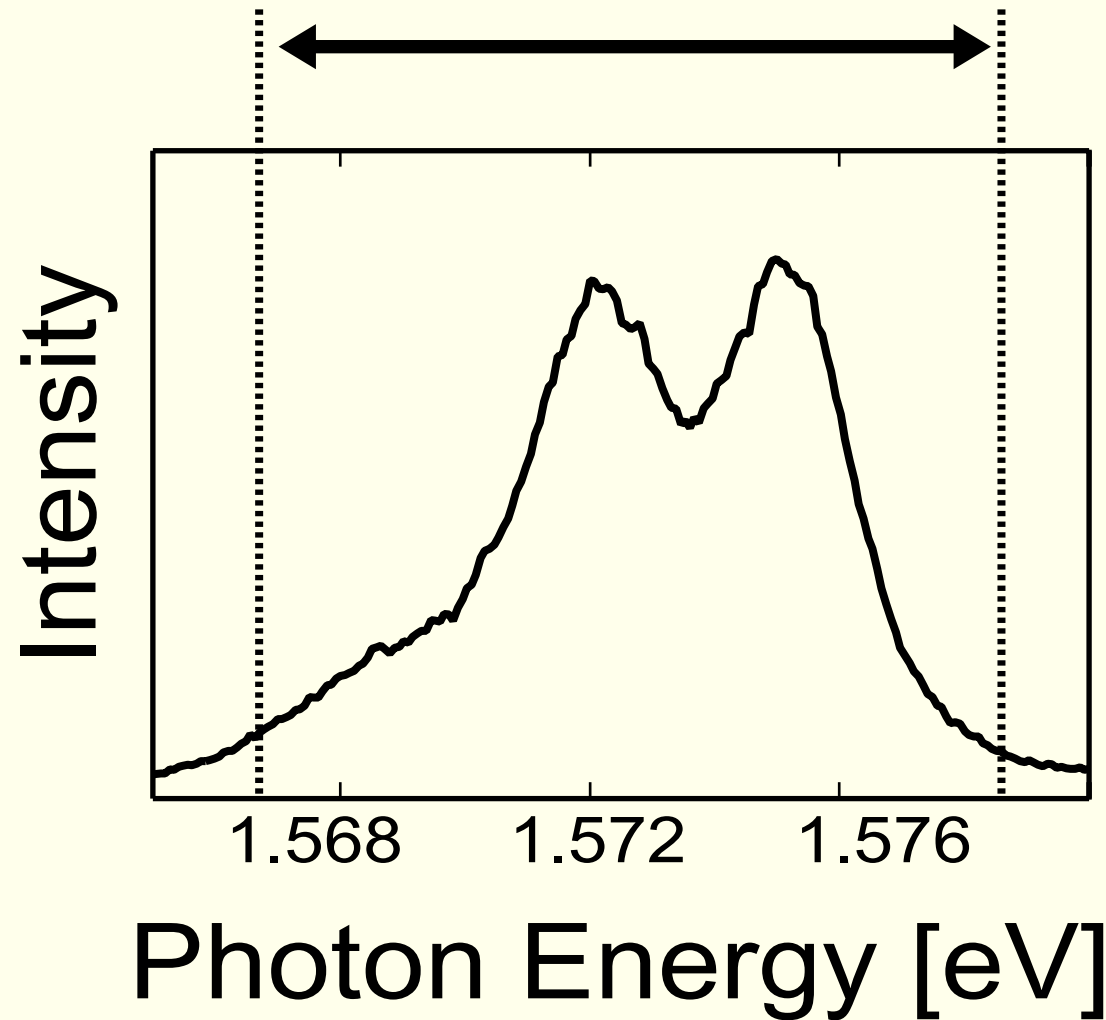
## 今後の課題

- ・ 偏光依存も含めた、振動子強度のより正確な見積もり  
(=全ての正孔バンドを考慮した計算)
- ・ 試料、励起場所を変えた測定

# # プローブに用いた領域

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integrated region

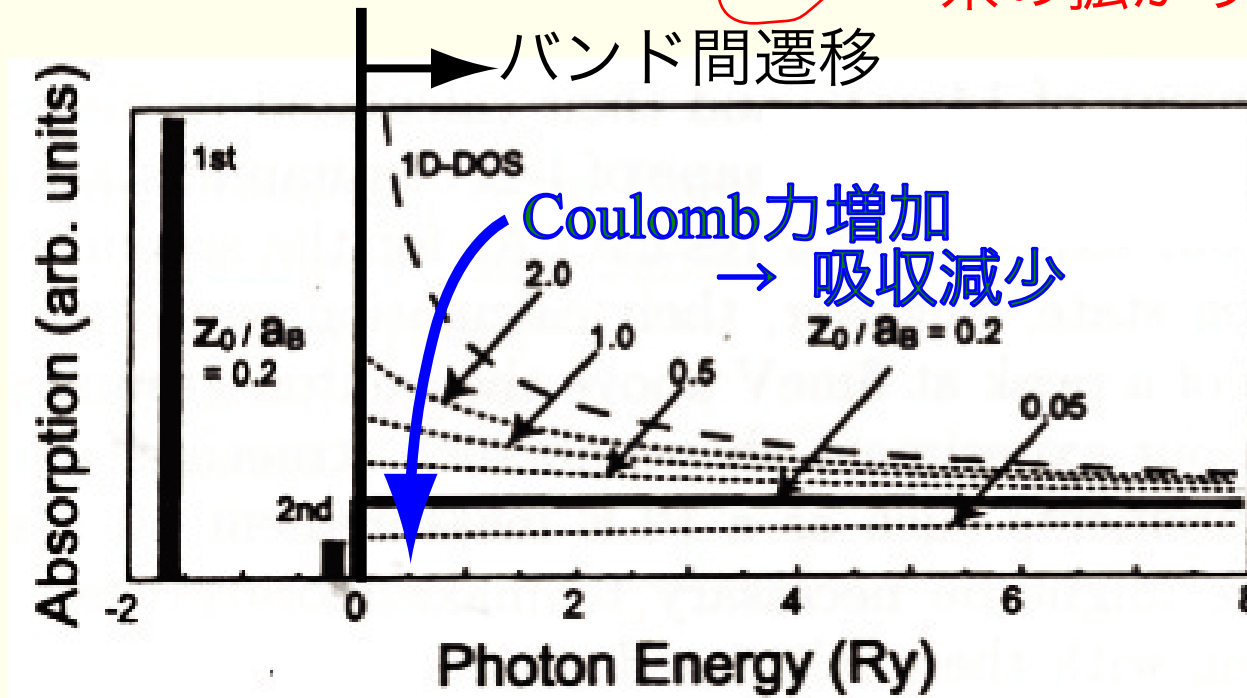


PL spectrum  
excited at 758[nm]  
(1.635[eV])

# # Ogawaらの計算結果

1次元系に対する光吸収の、Coulomb力を含めた数値計算

$E_b$  の発散を防ぐため、 $-\frac{e^2}{\epsilon(|z| + \underline{z_0})}$  というポテンシャルを用いる  
系の拡がり (wireの太さ)



Ogawa and Takagahara PRB 43 14325 (1991)

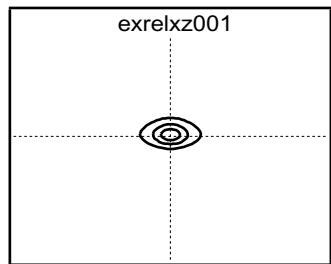
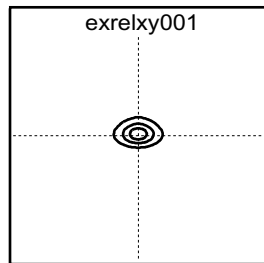
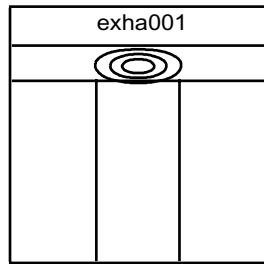
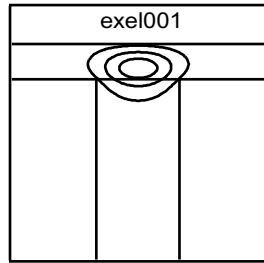
ゾンマーフェルト因子  $S_{1D} < 1$  は1次元系特有。cf.  $S_{2D}, S_{3D} > 1$

$S \equiv$  (Coulomb力を取り入れた計算) / (Coulomb力を無視した計算)

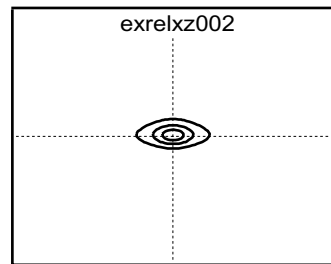
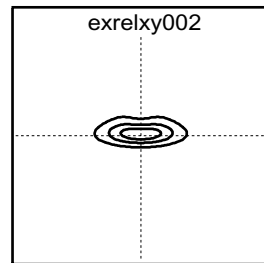
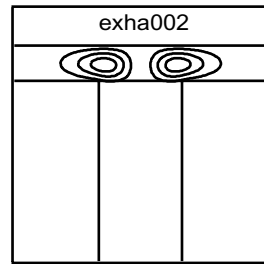
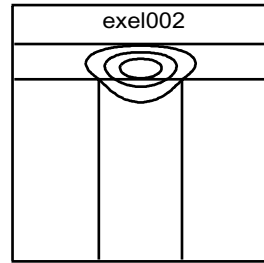


# # Szymanskaらの計算結果 -- 1-4

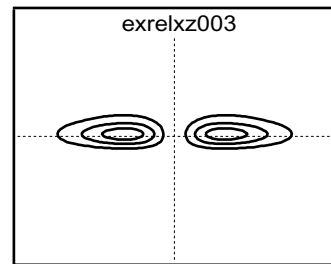
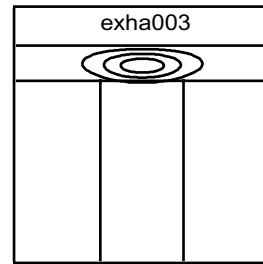
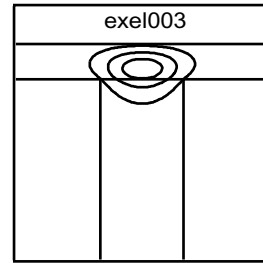
1



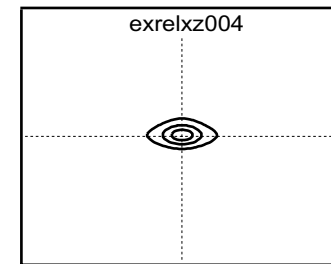
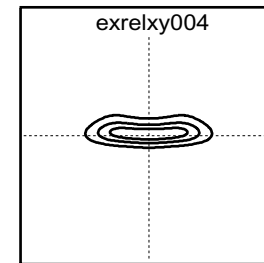
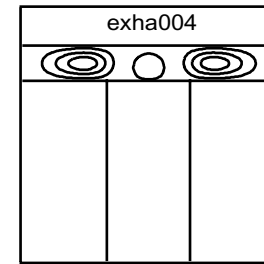
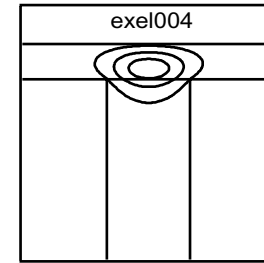
2



3

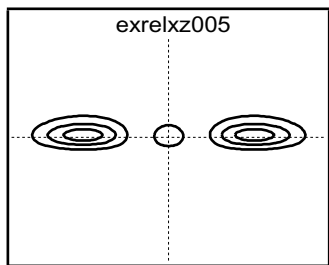
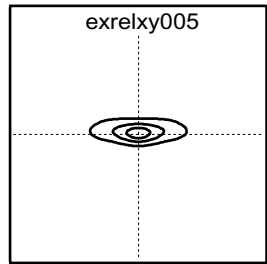
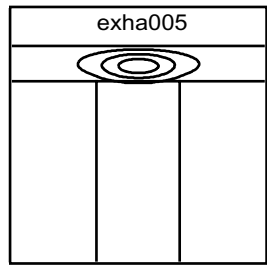
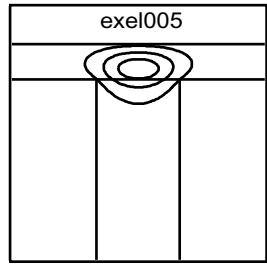


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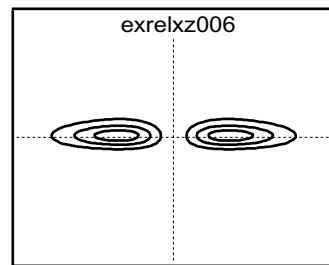
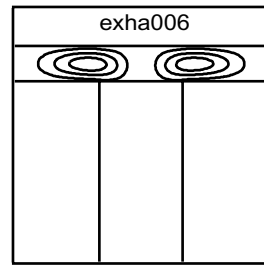
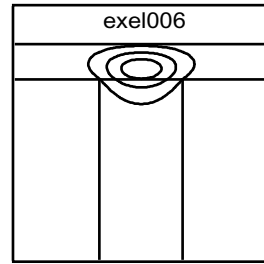


# # Szymanskaらの計算結果 -- 5-8

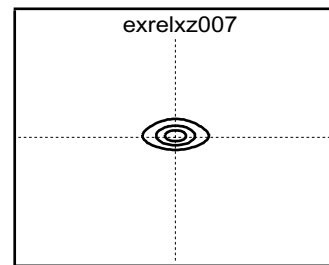
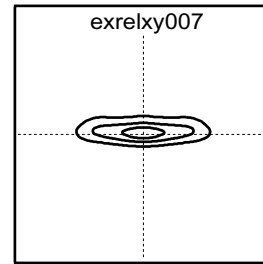
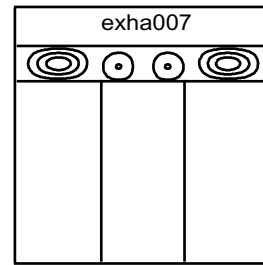
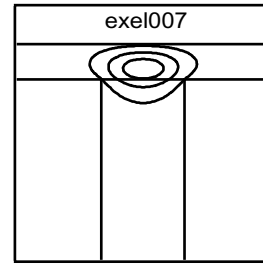
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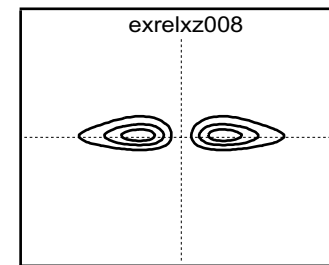
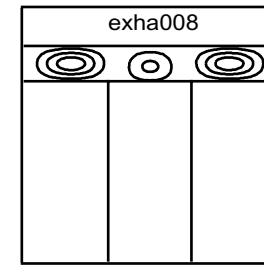
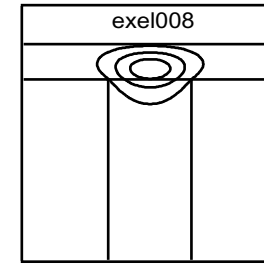
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7

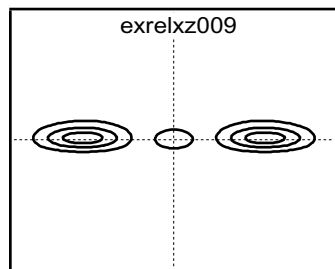
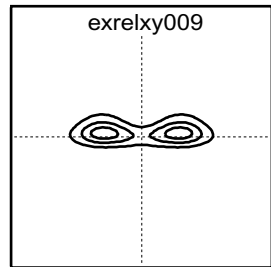
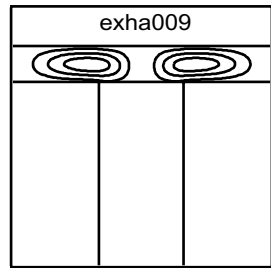
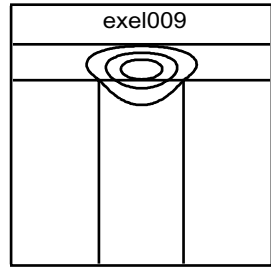


8

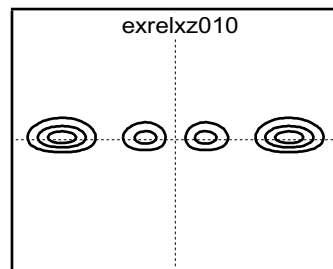
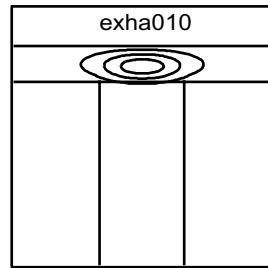
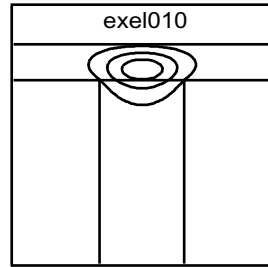


# # Szymanskaらの計算結果 -- 9-12

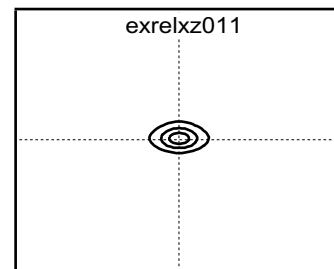
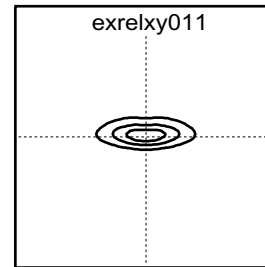
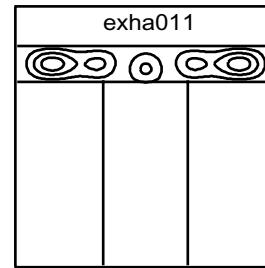
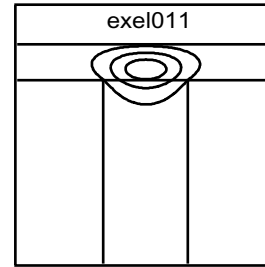
9



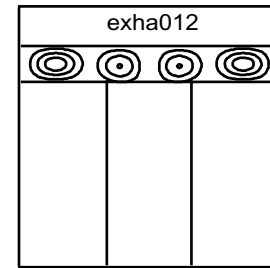
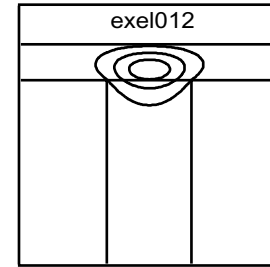
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11

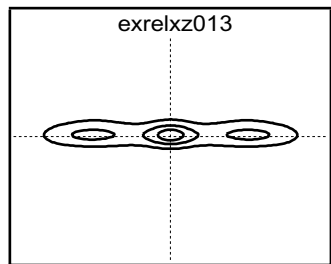
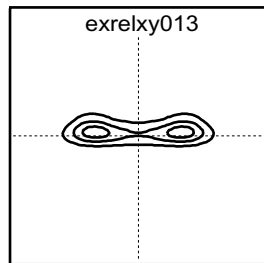
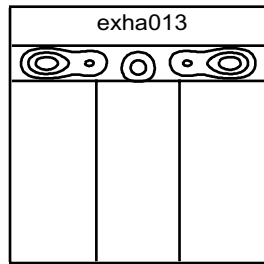
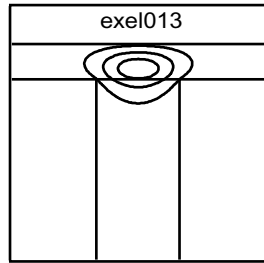


12

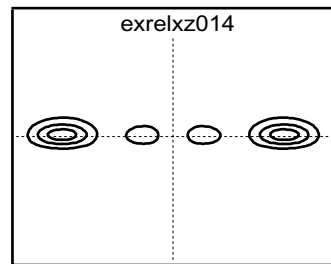
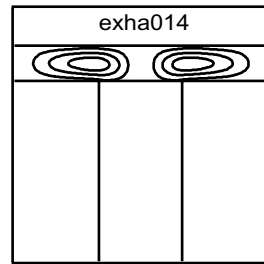
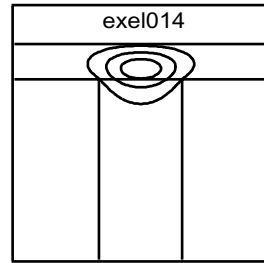


# # Szymanskaらの計算結果 -- 13-16

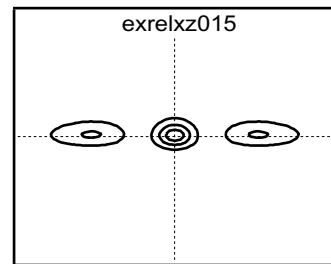
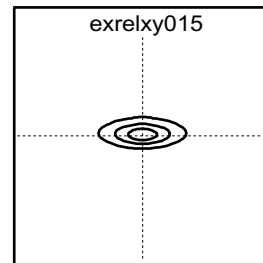
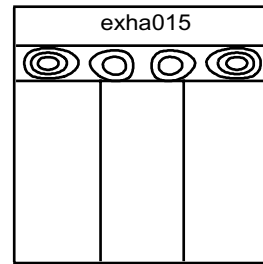
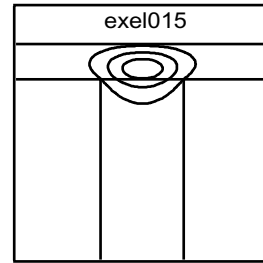
13



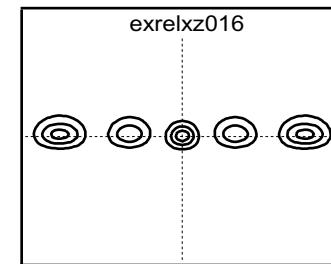
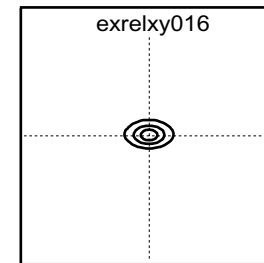
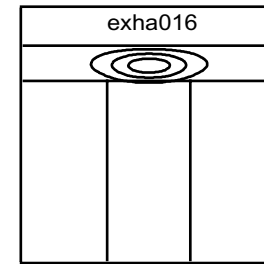
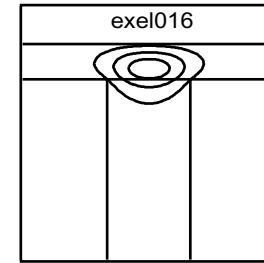
14



15

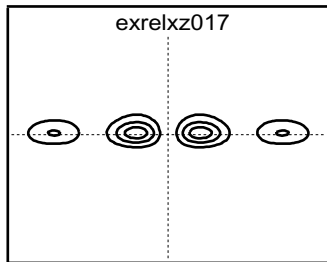
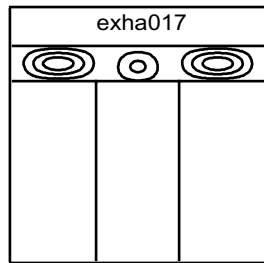
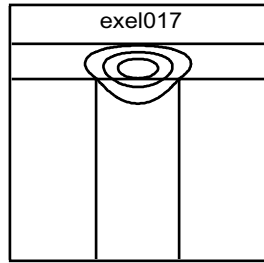


16

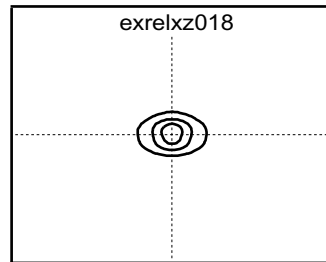
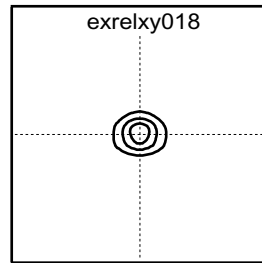
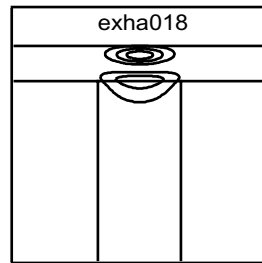
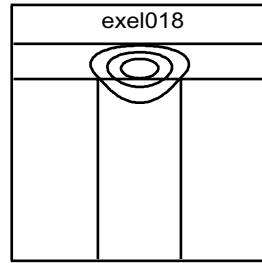


# # Szymanskaらの計算結果 -- 17-20

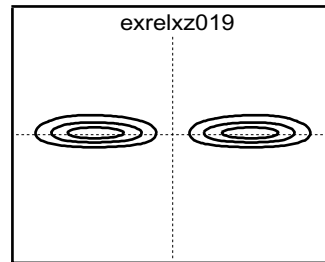
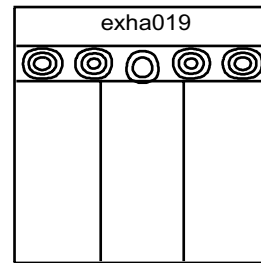
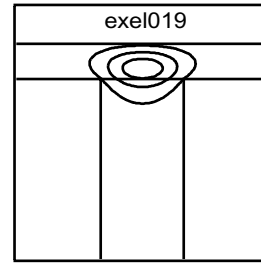
17



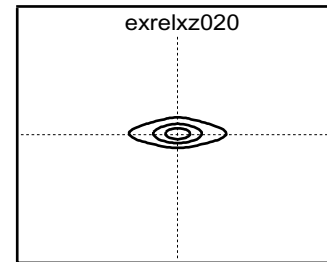
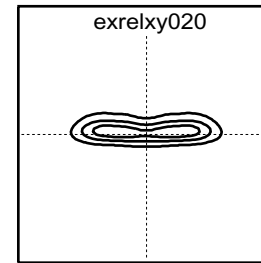
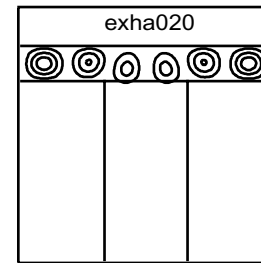
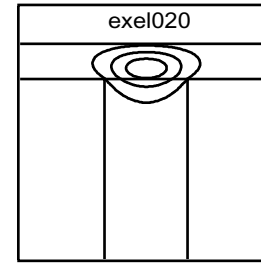
18



19

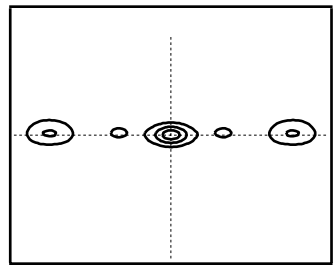
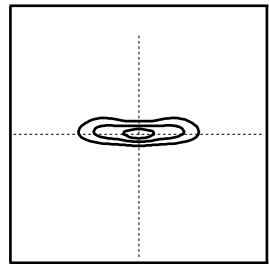
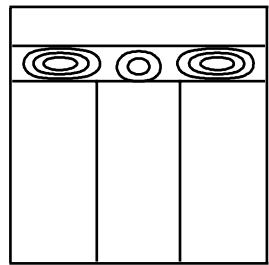
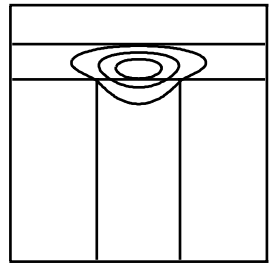


20

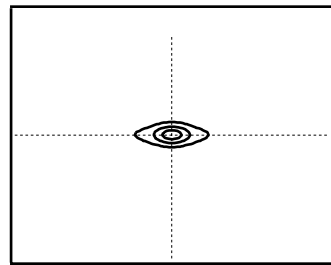
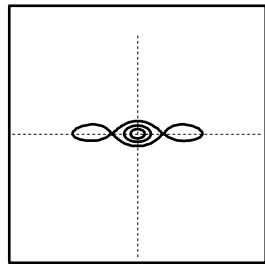
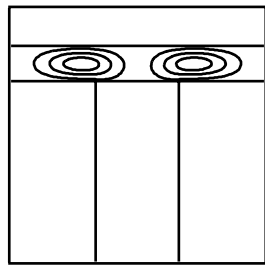
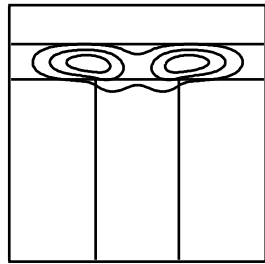


# # Szymanskaらの計算結果 -- 25-27, 98

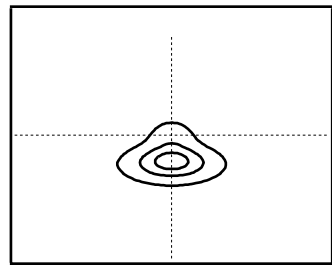
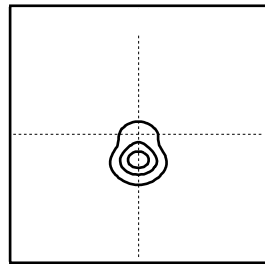
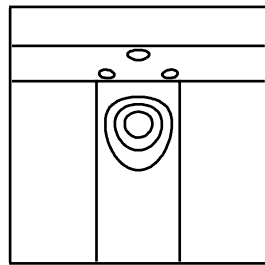
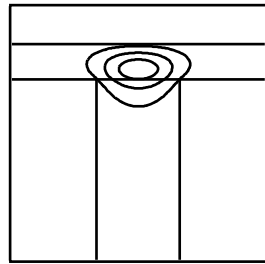
25



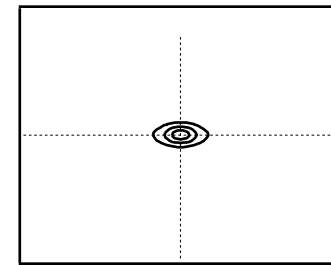
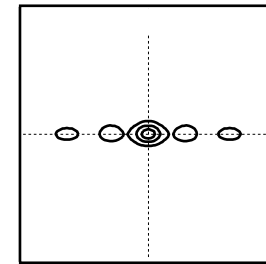
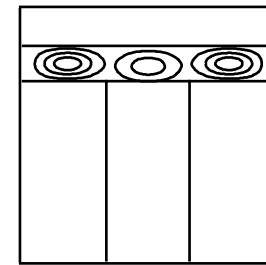
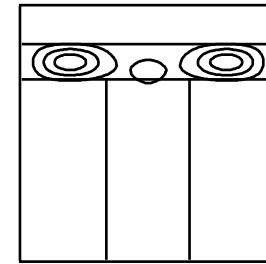
26



27



98



# # 計算結果 -- 振動子強度

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#	strength	exciton	hole
1	1.000e+00	g	g
2	7.889e-09	g	2nd
3	1.377e-32	2nd	g
4	4.496e-04	g	3rd
5	1.428e-01	3rd	g
6	2.221e-42	2nd	2nd
7	1.402e-09	g	4th
8	2.097e-33	2nd	3rd
9	1.200e-09	3rd	2nd
10	2.031e-32	4th	g
11	8.127e-04	g	5th
12	3.864e-42	2nd	4th
13	3.790e-04	3rd	3rd?
14	9.864e-42	4th	2nd
15	2.939e-07	3rd	4th
16	3.204e-01	5th	g
17	6.771e-34	4th	3rd
18	5.142e-02	?	?
19	1.241e-36	2nd	5th
20	8.917e-08	g	6th

# # 計算結果 -- 振動子強度

- 励起子の励起状態
- 正孔の基底状態
- エネルギーのズレ大  
(電子軽い→端の影響大)
- 振動子強度は大

#	strength	exciton	hole
1	1.000e+00	g	g
2	7.889e-09	g	2nd
3	1.377e-32	2nd	g
4	4.496e-04	g	3rd
5	1.428e-01	3rd	g
6	2.221e-42	2nd	2nd
7	1.402e-09	g	4th
8	2.097e-33	2nd	3rd
9	1.200e-09	3rd	2nd
10	2.031e-32	4th	g
11	8.127e-04	g	5th
12	3.864e-42	2nd	4th
13	3.790e-04	3rd	3rd?
14	9.864e-42	4th	2nd
15	2.939e-07	3rd	4th
16	3.204e-01	5th	g
17	6.771e-34	4th	3rd
18	5.142e-02	?	?
19	1.241e-36	2nd	5th
20	8.917e-08	g	6th



# # 計算結果 -- 振動子強度

- 励起子の励起状態
- 正孔の基底状態
- エネルギーのズレ大  
(電子軽い→端の影響大)
- 振動子強度は大

#	strength	exciton	hole
1	1.000e+00	g	g
2	7.889e-09	g	2nd
3	1.377e-32	2nd	g
4	4.496e-04	g	3rd
5	1.428e-01	3rd	g
6	2.221e-42	2nd	2nd
7	1.402e-09	g	4th
8	2.097e-33	2nd	3rd
9	1.200e-09	3rd	2nd
10	2.031e-32	4th	g
11	8.127e-04	g	5th
12	3.864e-42	2nd	4th
13	3.790e-04	3rd	3rd?
14	9.864e-42	4th	2nd
15	2.939e-07	3rd	4th
16	3.204e-01	5th	g
17	6.771e-34	4th	3rd
18	5.142e-02	?	?
19	1.241e-36	2nd	5th
20	8.917e-08	g	6th

- 励起子の基底状態
- 正孔の励起状態
- エネルギーのズレ小  
(正孔重い→端の影響小)
- 振動子強度は小