Transport in Quantum Cascade Detectors

C. Koeniguer, A. Gomez, V. Berger

- "Materiaux et phenomenes quantiques", Univ. Paris 7, 2 pl. Jussieu, 75005 Paris
- Thales Research and Technology, Domaine de Corbeville, 91404 Orsay cedex France

N. Péré Laperne, L.A. De Vaulchier, Y. Guldner

- Laboratoire Pierre Aigrain, Ecole Normale Supérieure, 24 Rue Lhomond, 75005 PARIS

Samples are grown, processed and characterized by the Thales group (P. Bois, E. Costard, X. Marcadet, A. Nedelcu, N. Brière de l'Isle…)

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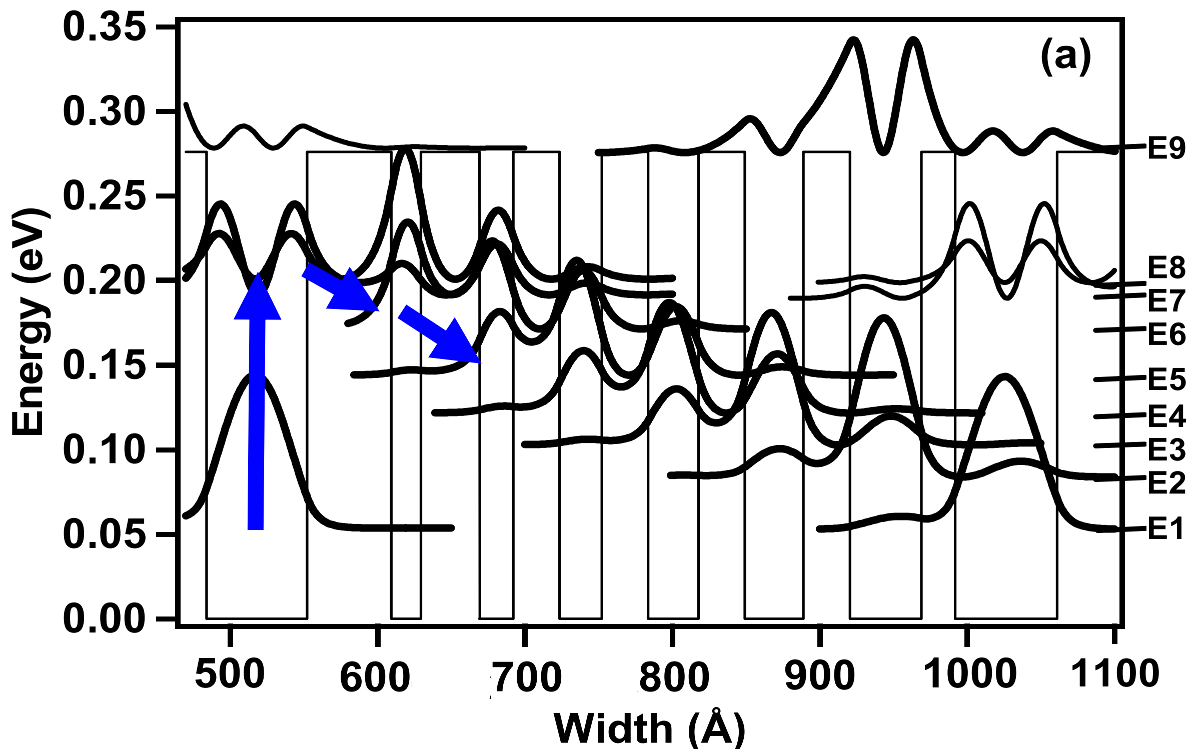
Outline

- General context and principle
- Dark transport modeling
- Magneto-transport measurements
- Conclusion



- Barriers : AlGaAs, typically 22 Å, % Al = 34%
- QWs : GaAs, between 20 and 80 Å, doping 5. 10^{11} or 10^{12} cm^{-2}
- Number of periods : 20 or 40
- THALES patent

QWIPs

•V>0 for electron collection

•Significative dark current

•Capacitance saturation in large area focal plane arrays, integration time…

QW photovoltaic detectors

•V=0 no dark current

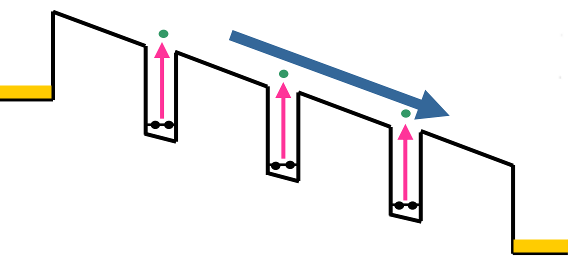
•Low quantum efficiency (bad electron extraction or fast relaxation to fundamental)

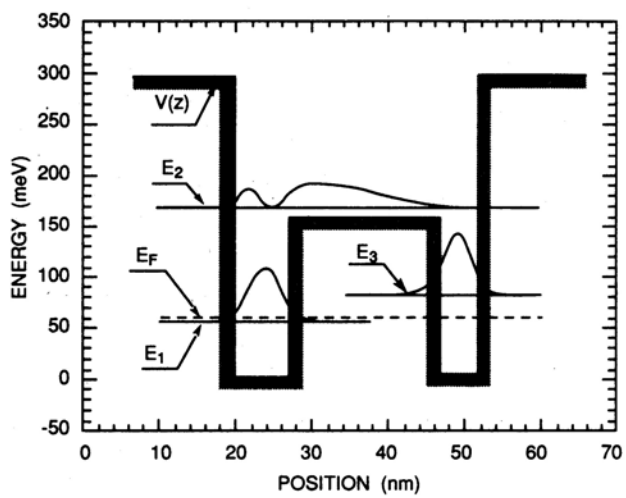
•Low response

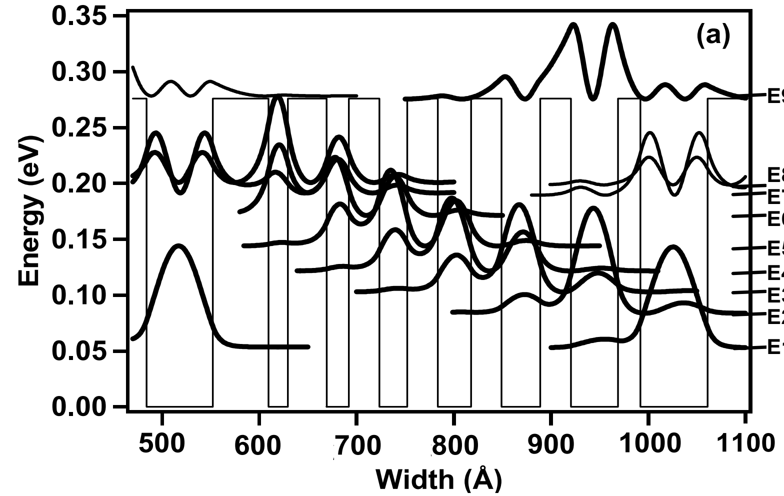
QCDs

•V=0 no dark current

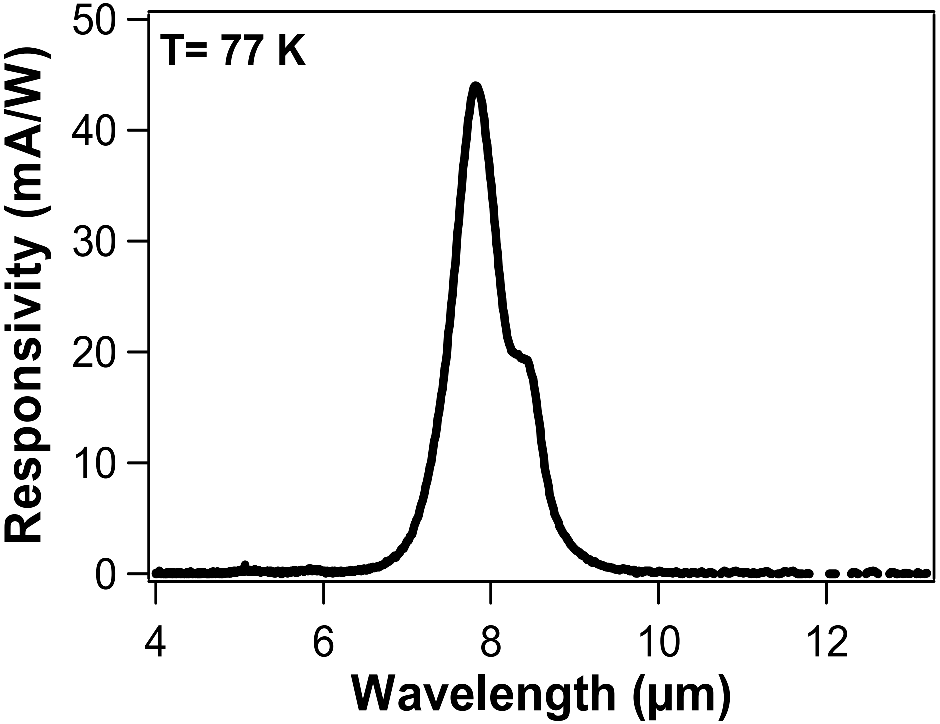
•Good quantum efficiency thanks to the cascade scheme (optimization of a good matrix element and a good electron extraction)

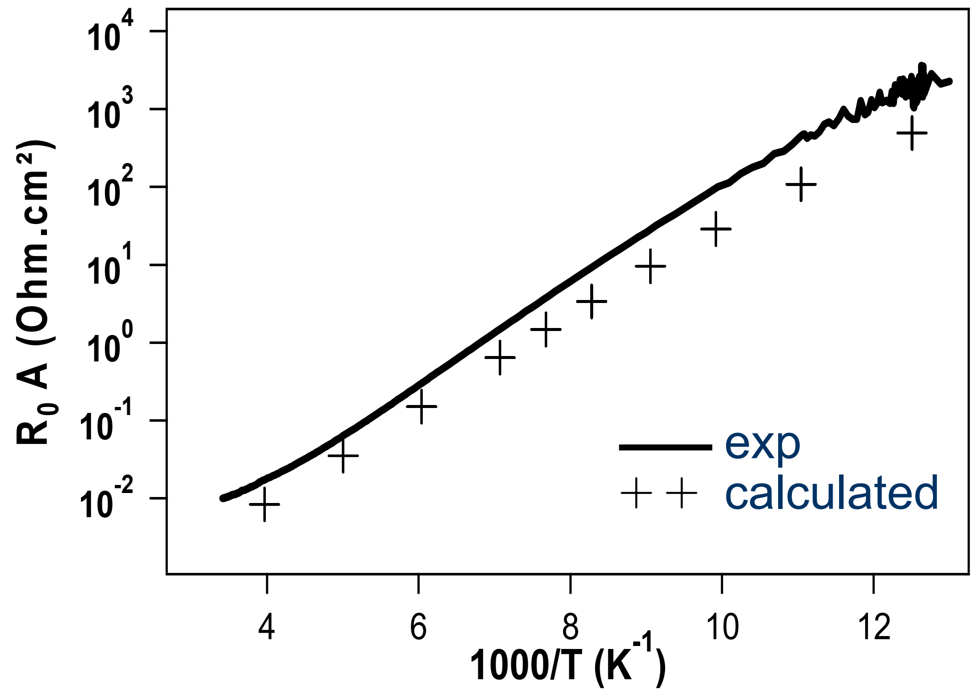






$$D^* = R(\lambda)\sqrt{\frac{R_0 A}{4 k_B T}}$$





R = 44 mA/W at 77 K (8µm)

R_0A (50K) ≈ 3 10^5 Ω.cm²

R_0A (77K) ≈ 10^3 Ω.cm²

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- The quantum cascade detector is nothing but a QWIP, in which the applied electric field has been replaced by a quantum heterostructure built-in electric field

- QWIPs have two versions : photoconductive (the wellknown classical QWIP) and photovoltaïc (QCD) with no dark current

- The photovoltaïc version can be directly compared to other photovoltaïc detectors (MCTs, T2SLs) using the same ROIC

- QWIPs and QCDs rely on the same technological skills and benefit from the same advantages :
  - Easy cut off choice by quantum design and high cut off uniformity, (Uniformity is not only a matter of III-V materials but also a matter of intersubband versus interband transitions)
  - GaAs/AlGaAs material : no need for passivation, no 1/f

<u>Two directions for improvement</u> :

1) Increase quantum efficiency (innovative QCD designs and electromagnetic structures)

2) Decrease the noise figure (increase the R0A)

Theoretical modeling enables the electronic transport in these complex heterostructures to be understood

Experiments under magnetic field allows the validation of the modeling

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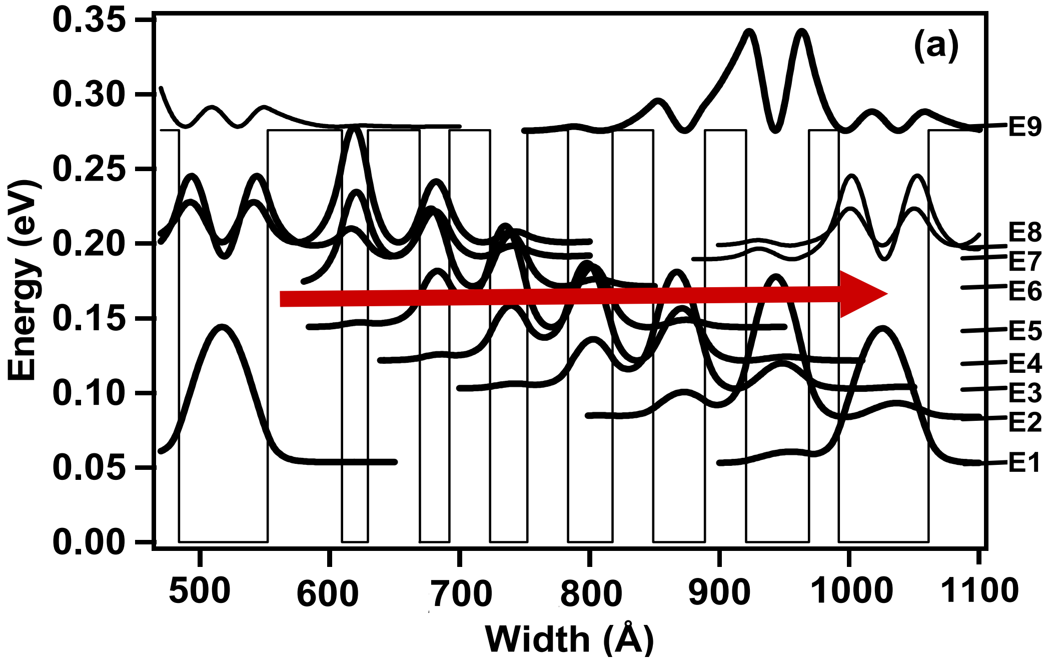
How does the current flow in a quantum cascade structure ?
Through which subbands go electrons ?
How to calculate the R0A ? (resistance at 0V – determinates the Johnson noise)
Very small biases : neither field nor Coulomb effect in the structure



We will study all the possible scattering events between two subbands

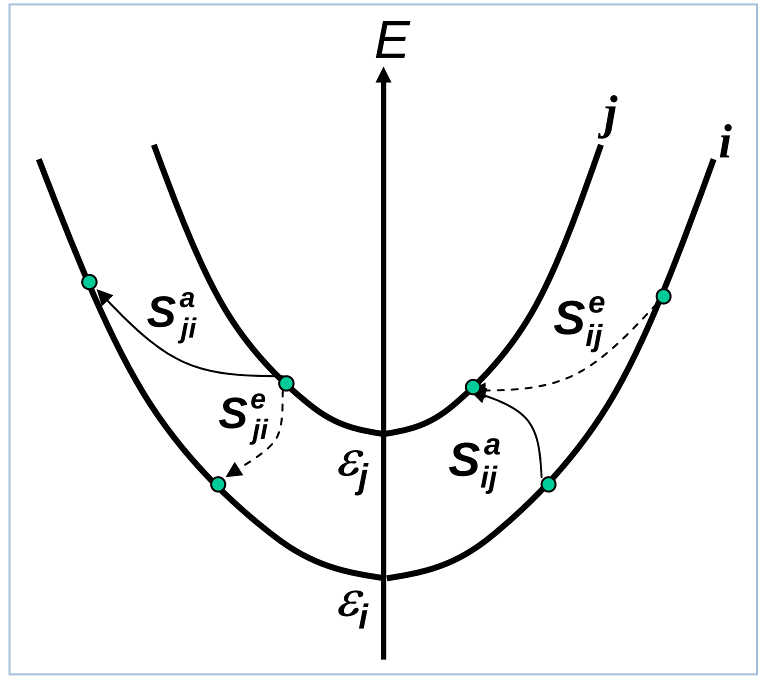
Predominant scattering process : Electron/LO-phonons interactions

Neglected scattering mechanisms :
- Interface roughness scattering
- Acoustic phonons scattering
- Electron-electron interactions

$$G_{ij}^{a} = \int_{\varepsilon_j - \hbar\omega_{LO}}^{\infty} S_{ij}^{a}(E) f(E)\left(1 - f(E + \hbar\omega_{LO})\right) n_{opt} D(E) dE$$

$$G_{ij}^{e} = \int_{\varepsilon_j + \hbar\omega_{LO}}^{\infty} S_{ij}^{e}(E) f(E)\left(1 - f(E - \hbar\omega_{LO})\right)(1 + n_{opt}) D(E) dE$$

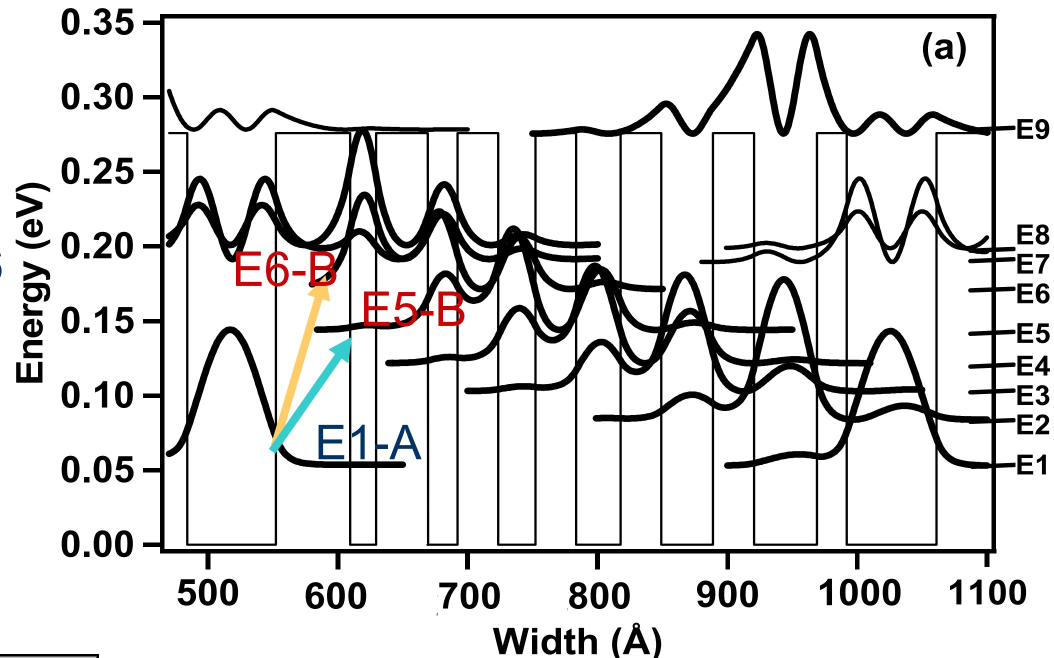
- Sij* single state transition rate to subband j
- Gij global tr. rate from subband i to subband j



→ Evaluation of the R0A parameter

*Ferreira and Bastard, *Phys. Rev. B*, **40**, 1074 (1989)

- At 80 K, two dominant cross transitions between two cascades : E1-E5 and E1-E6
- These transitions play a key role in the I(V) charcateristics



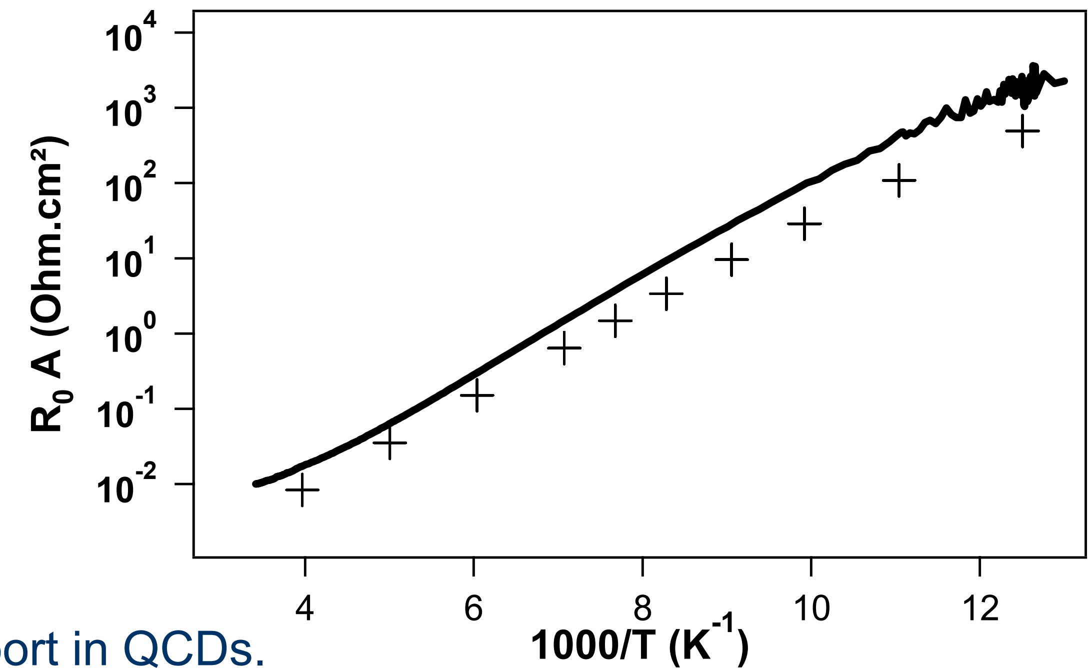
G_{ij} (m-2s-1)	3_B	4_B	5_B	6_B	7_B	8_B
1_A	6,8E+17	3,0E+18	5,1E+18	5,0E+18	3,5E+18	2,3E+18
2_A		1,1E+18	4,6E+18	1,3E+18	8,0E+17	5,6E+17
3_A			1,3E+18	3,0E+17	1,6E+17	1,1E+17
4_A				1,5E+17	4,4E+16	2,8E+16
5_A					1,8E+16	6,9E+15
6_A						6,6E+15

- In opposite to a QWIP, a QCD can be described by a simple model, for two reasons :
    - Only two-dimensional states (no 3D to 2D capture). Matrix elements can be simply calculated.
    - Neither field nor Coulomb effects.

•The resistance of a QCD is entirely determined by a few electron – LO phonon transition rates Gij.

- Magnetic field enables to play with these transition rates.

- Magnetic field experiments offer an alternative way to understand the transport in QCDs.



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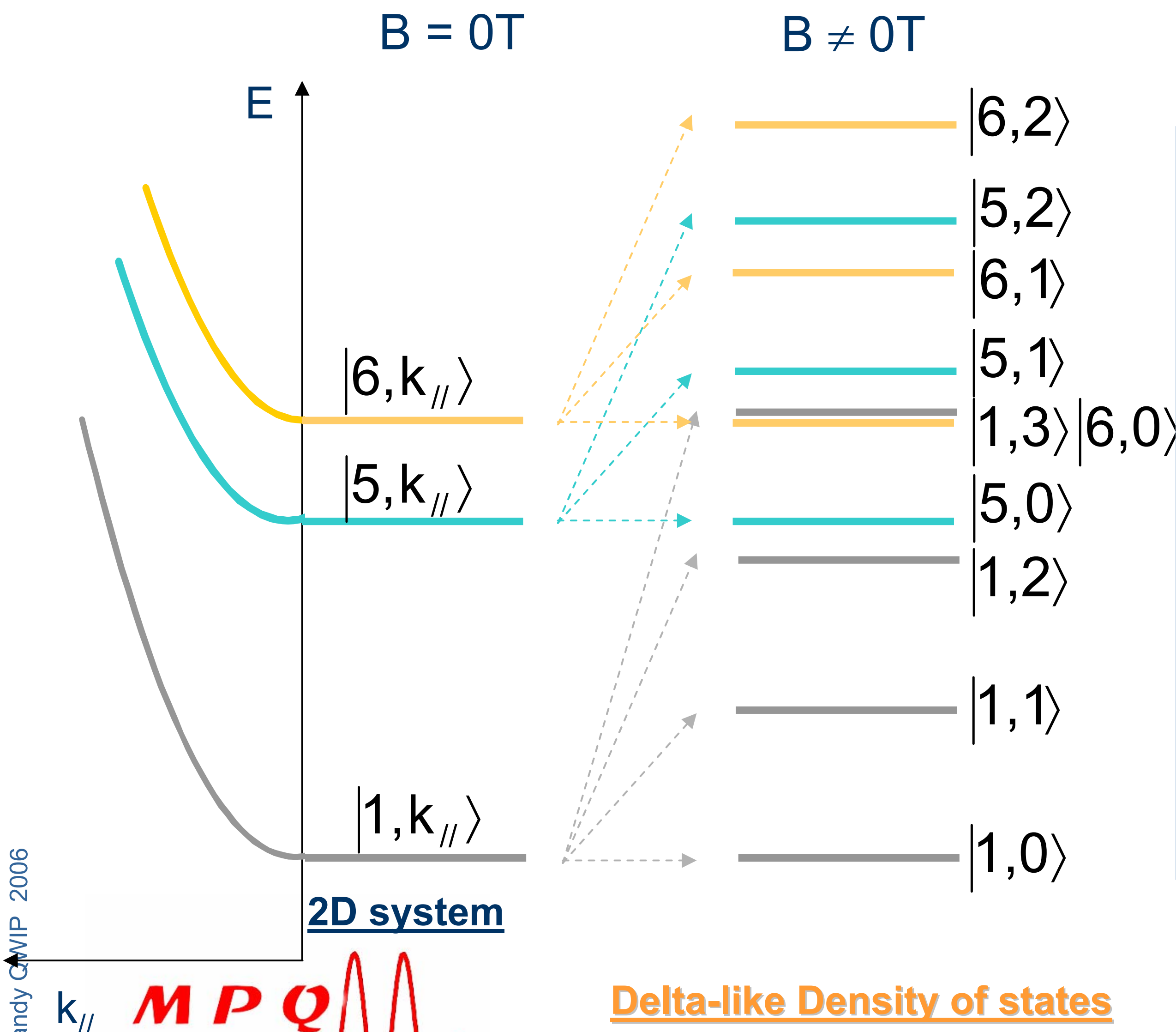


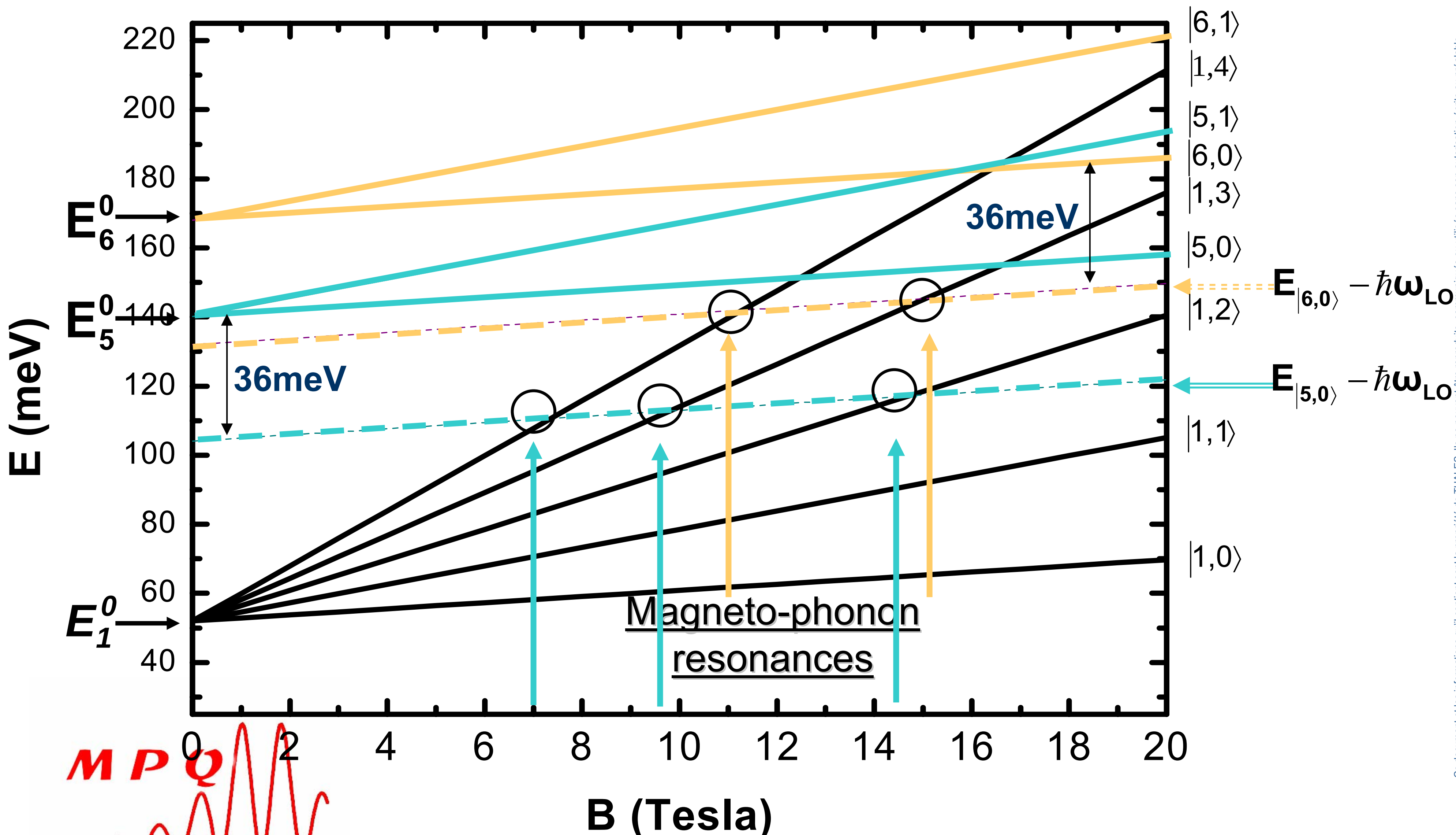
Under B
Each subband splits into p discrete energy levels

p landau levels

$$E_{|n,p\rangle} = E_n^0 + \left(\frac{1}{2} + p\right)\hbar\omega_c$$

$$\hbar\omega_c = \frac{\hbar eB}{m^*} \ : \text{ cyclotron energy}$$

Delta-like Density of states


E (meV)
B (Tesla)
220
200
180
160
140
120
100
80
60
40
0
2
4
6
8
10
12
14
16
18
20
E_6^0
E_5^0
E_1^0
36meV
36meV
|6,1⟩
|1,4⟩
|5,1⟩
|6,0⟩
|1,3⟩
|5,0⟩
|1,2⟩
|1,1⟩
|1,0⟩
$E_{|6,0\rangle} - \hbar\omega_{LO}$
$E_{|5,0\rangle} - \hbar\omega_{LO}$
Magneto-phonon resonances

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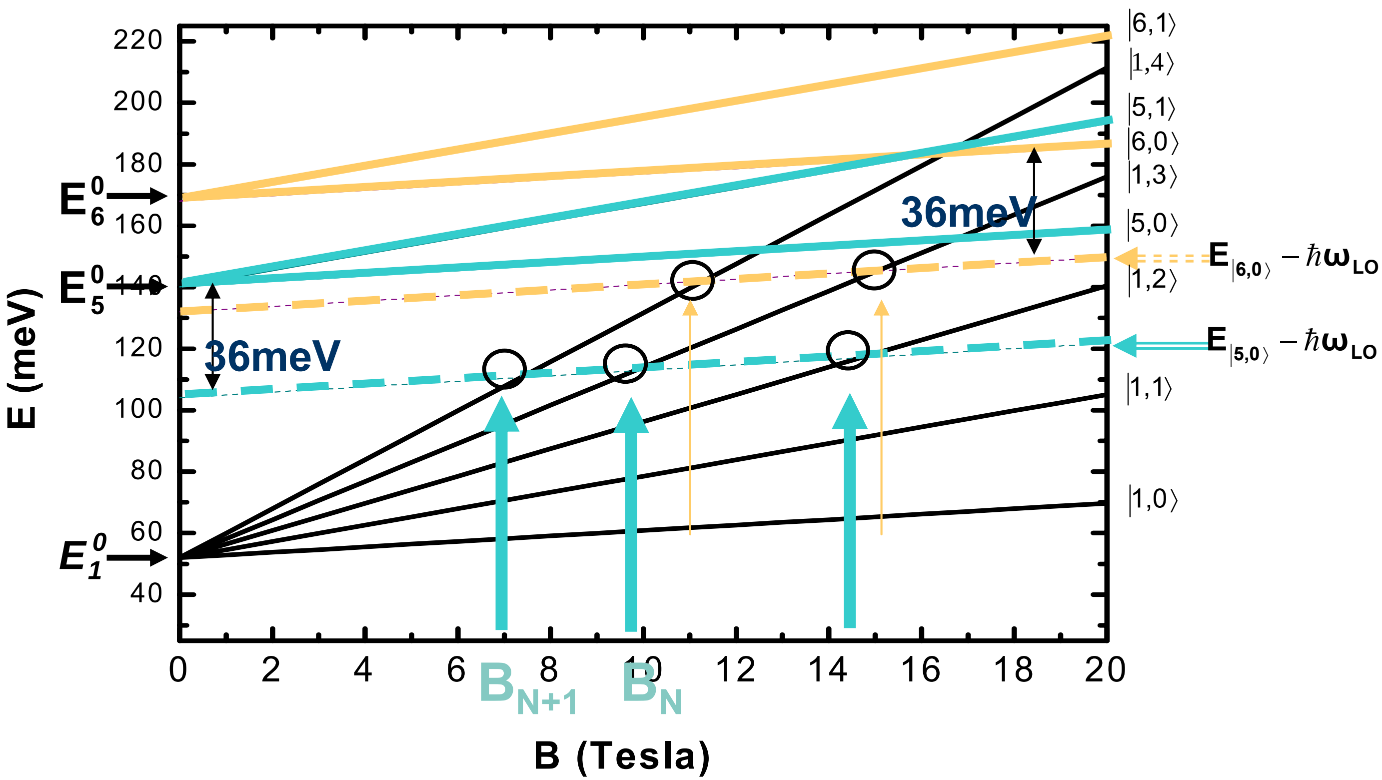
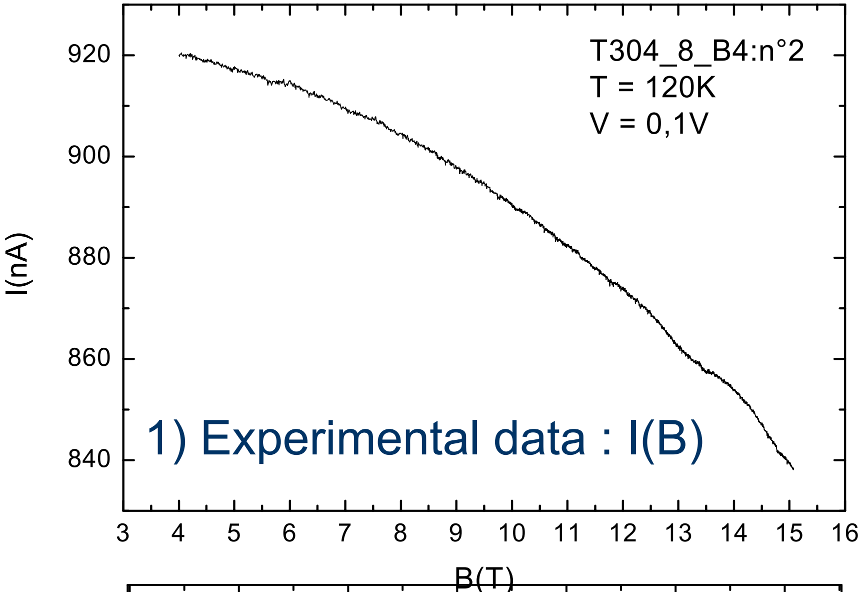
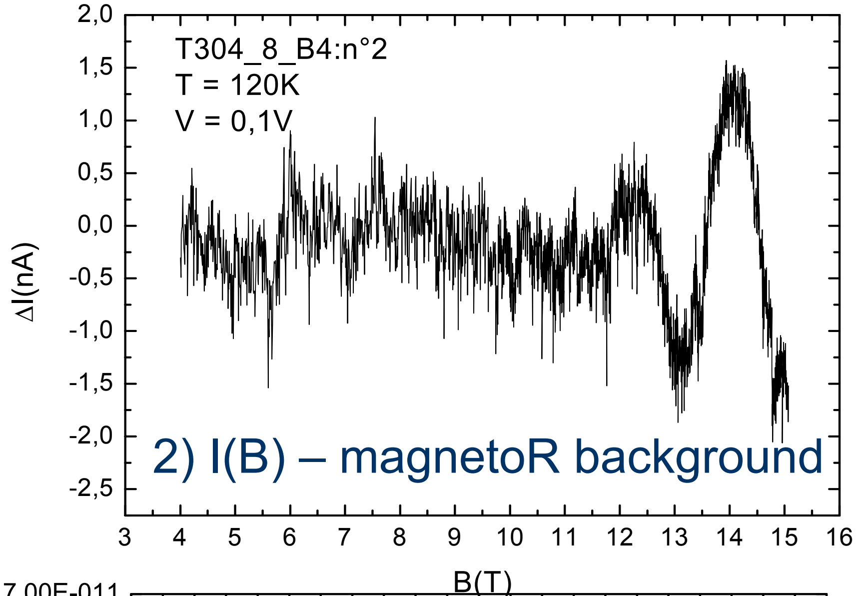


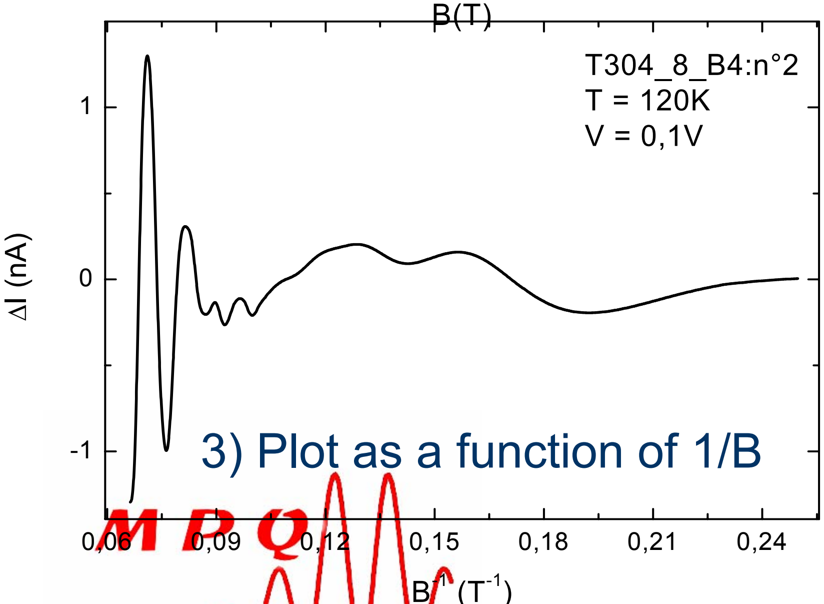
Magneto-resonances appear periodically as a function of 1/B

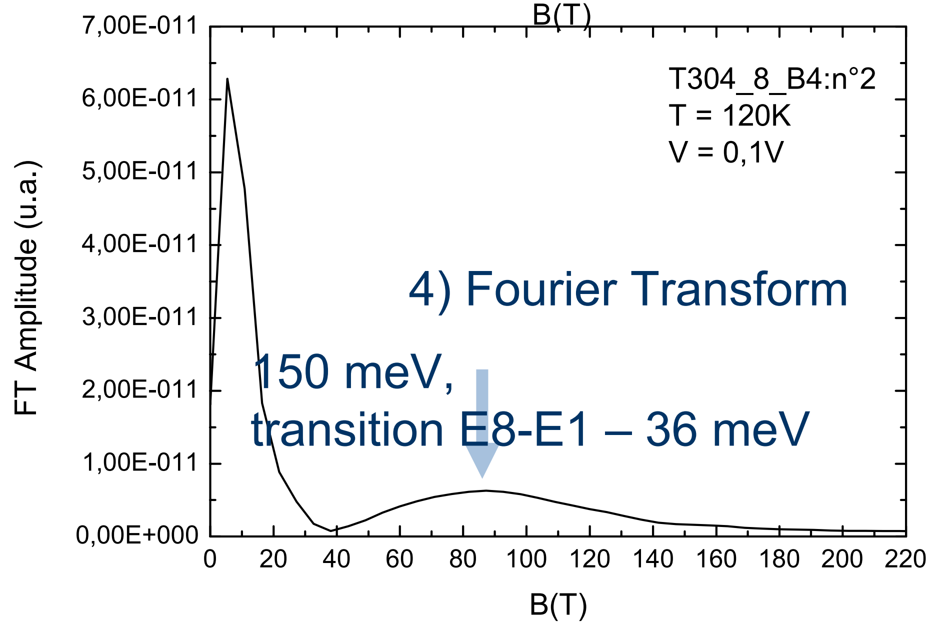
$$T = \frac{1}{B_{N+1}} - \frac{1}{B_N} = \frac{\hbar e}{m^*\left(\Delta E^* - \hbar\omega_{LO}\right)}$$

T304_8_B4– 120K

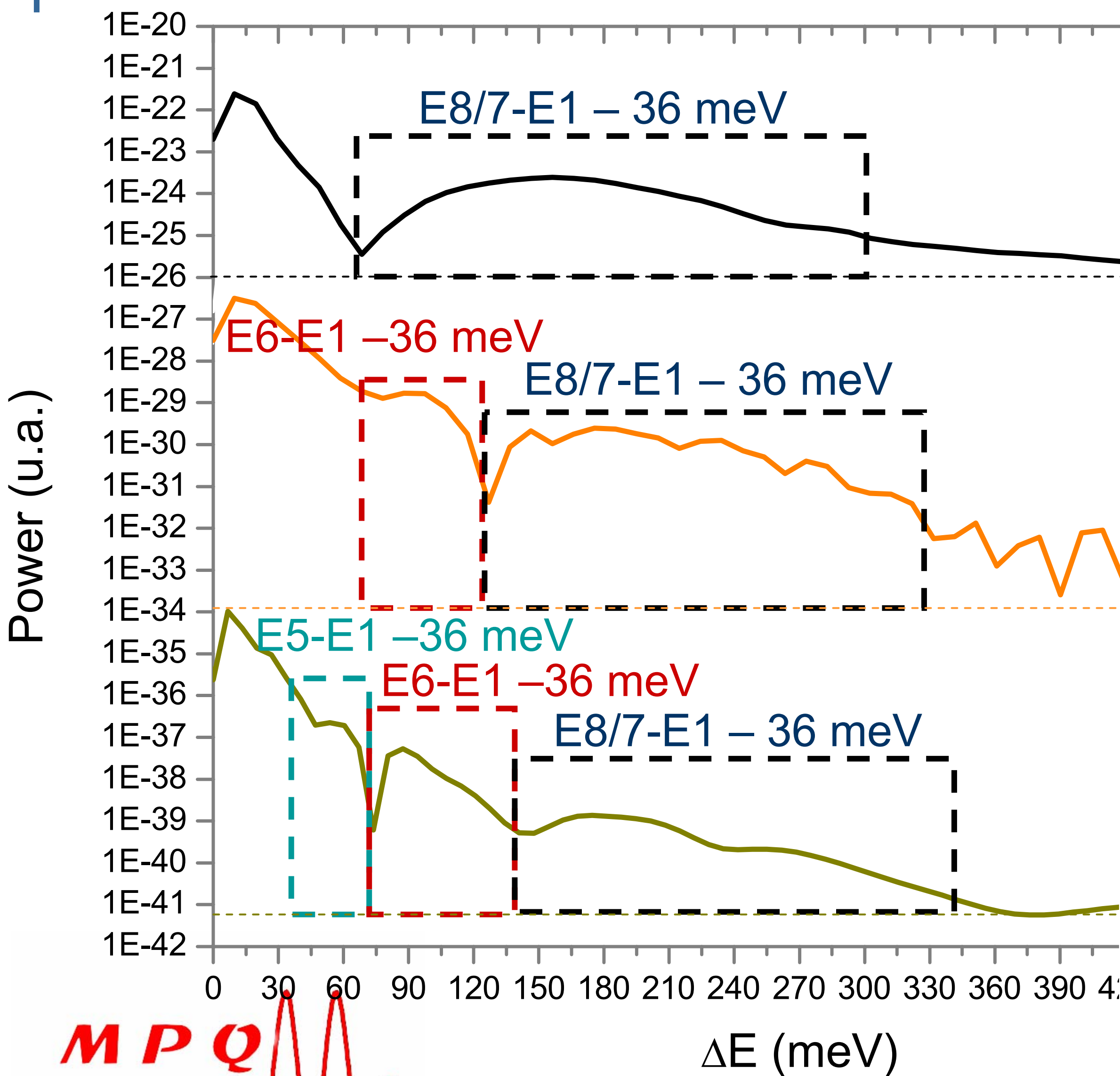


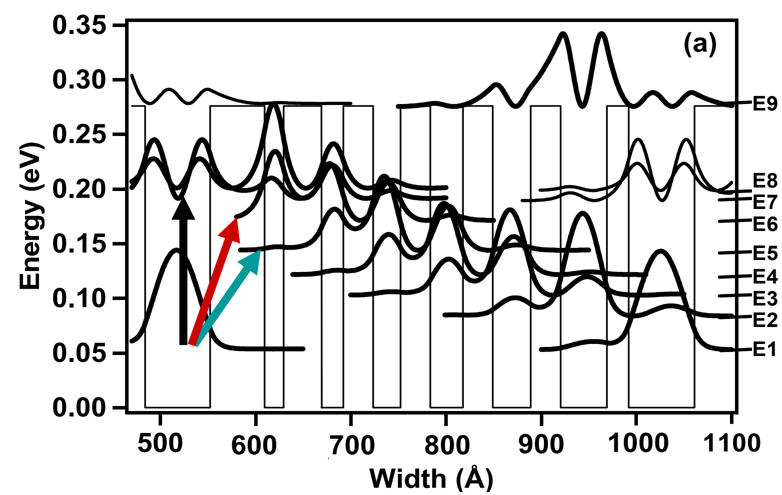






QCDs under magnetic field (4)





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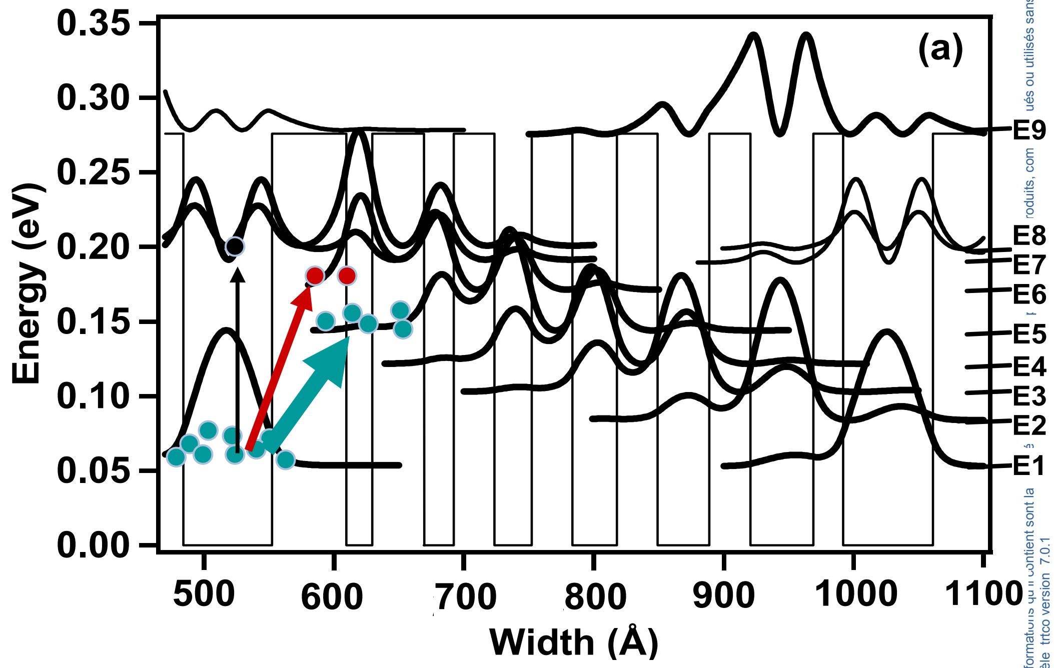
E8, E7 and E6 have good matrix elements, but are empty
E5 has a low matrix elements, but is populated

40 K 80 K 120 K

tau inter	T303			
Gij ($m^{-2}s^{-1}$)		40K	80K	120K
1A	1B	3,15569E+12	5,44E+14	2,73876E+15
1A	2B	3,72274E+14	6,40E+16	3,43888E+17
1A	3B	3,157E+15	6,76E+17	4,18894E+18
1A	4B	1,525E+15	3,01E+18	3,93265E+19
1A	5B	**9,184E+13**	5,10E+18	2,09209E+20
1A	6B	1,31743E+12	**5,03E+18**	8,71532E+20
1A	7B	25627674858	**3,49E+18**	**2,033E+21**
1A	8B	2898846646	2,32E+18	**2,458E+21**



E6 is now populated too
and has the best matrix elements

40 K 80 K 120 K

tau inter	T303			
Gij ($m^{-2}s^{-1}$)		40K	80K	120K
1A	1B	3,15569E+12	5,44E+14	2,73876E+15
1A	2B	3,72274E+14	6,40E+16	3,43888E+17
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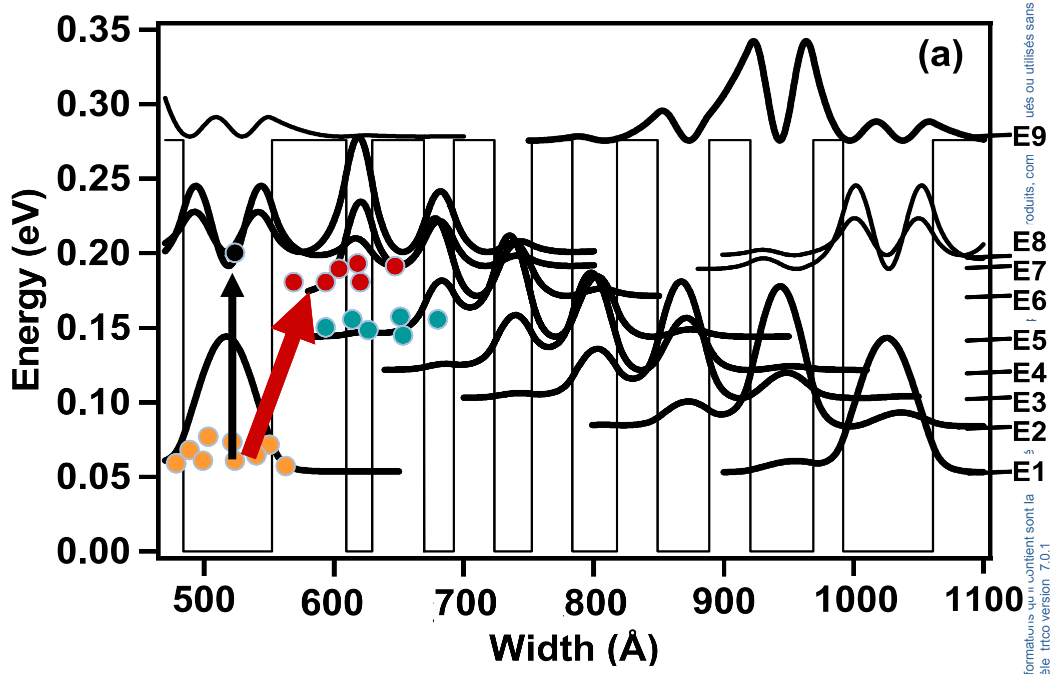

E7 and E8 are now populated
and have the best matrix elements

40 K 80 K **120 K**

tau inter	T303			
Gij ($m^{-2}s^{-1}$)		**40K**	**80K**	**120K**
1A	1B	3,15569E+12	5,44E+14	2,73876E+15
1A	2B	3,72274E+14	6,40E+16	3,43888E+17
1A	3B	3,157E+15	6,76E+17	4,18894E+18
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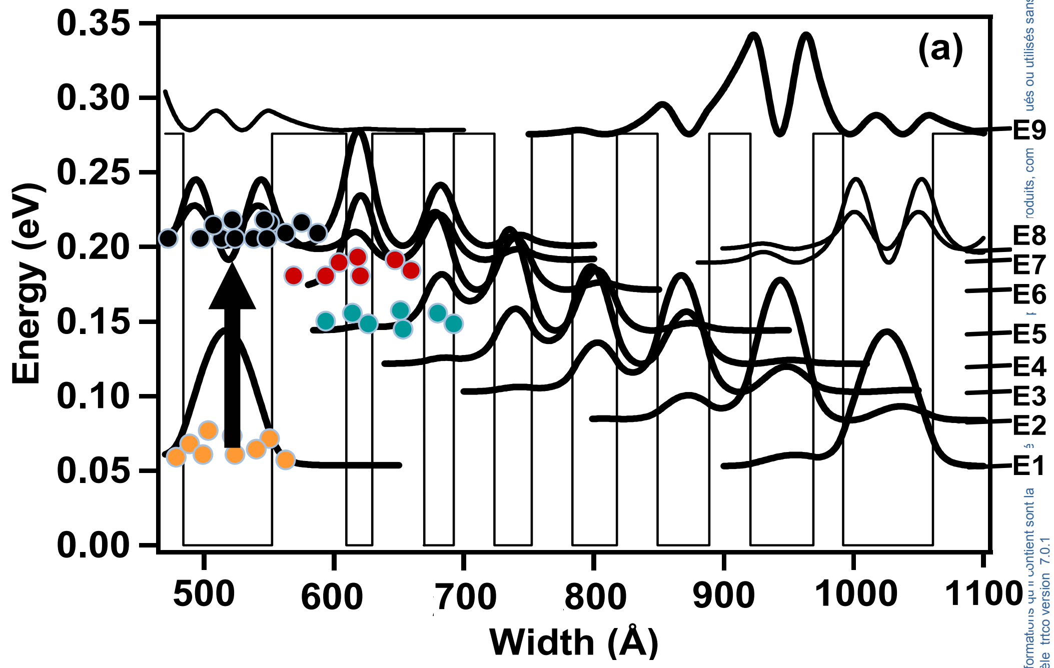

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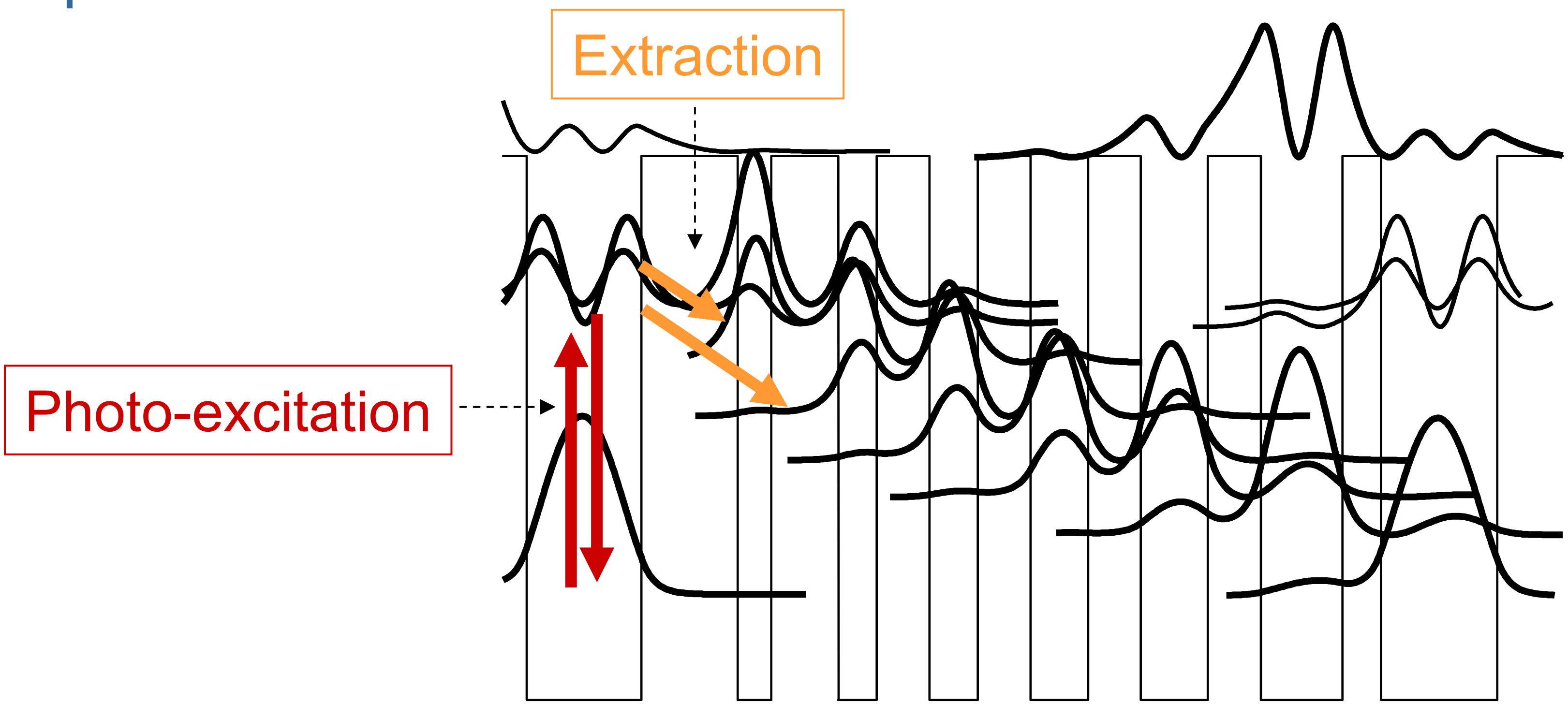
Design of a QCD:

- Good quantum efficiency (high electromagnetic matrix element)
- High resistance (avoid cross transitions : depends on the temperature of the detector)
- Magnetic field experiments help the design by the identification of the relevant cross transitions
- The optimal design highly depends on the working temperature of the focal plane array
- The extraction of photo-excited electrons can also be analysed by the analysis of magneto-photoresponse



- Modification of the E7 – E6 and E7 – E5 transfer times with a magnetic field
- Modification of the extraction of photo-excited electrons
- Analysis of internal quantum efficiency

Thank you for your attention