How is silicon-28 a semiconductor vacuum?

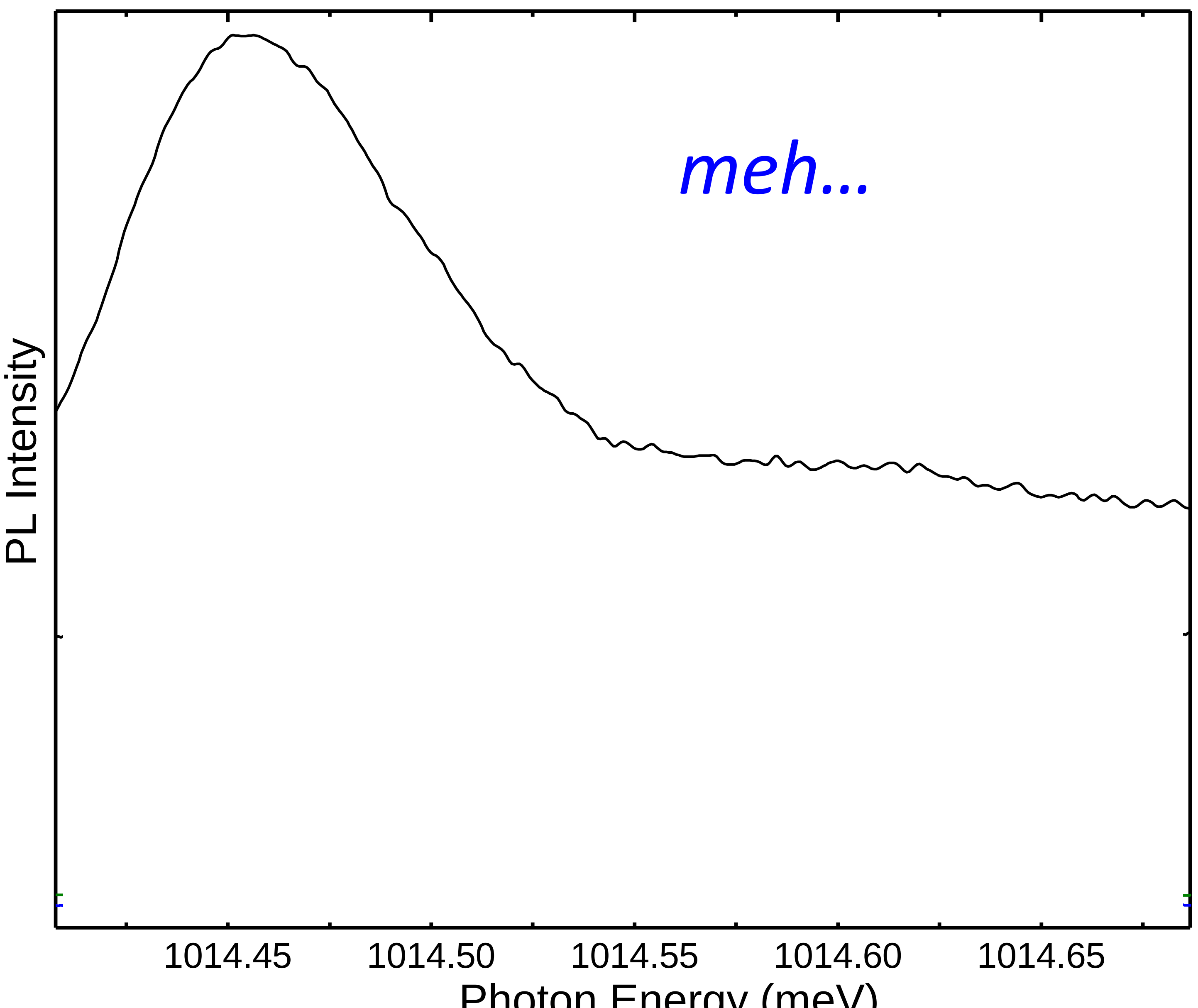
Mike Thewalt

Department of Physics (emeritus since Sept. 1, 2018)

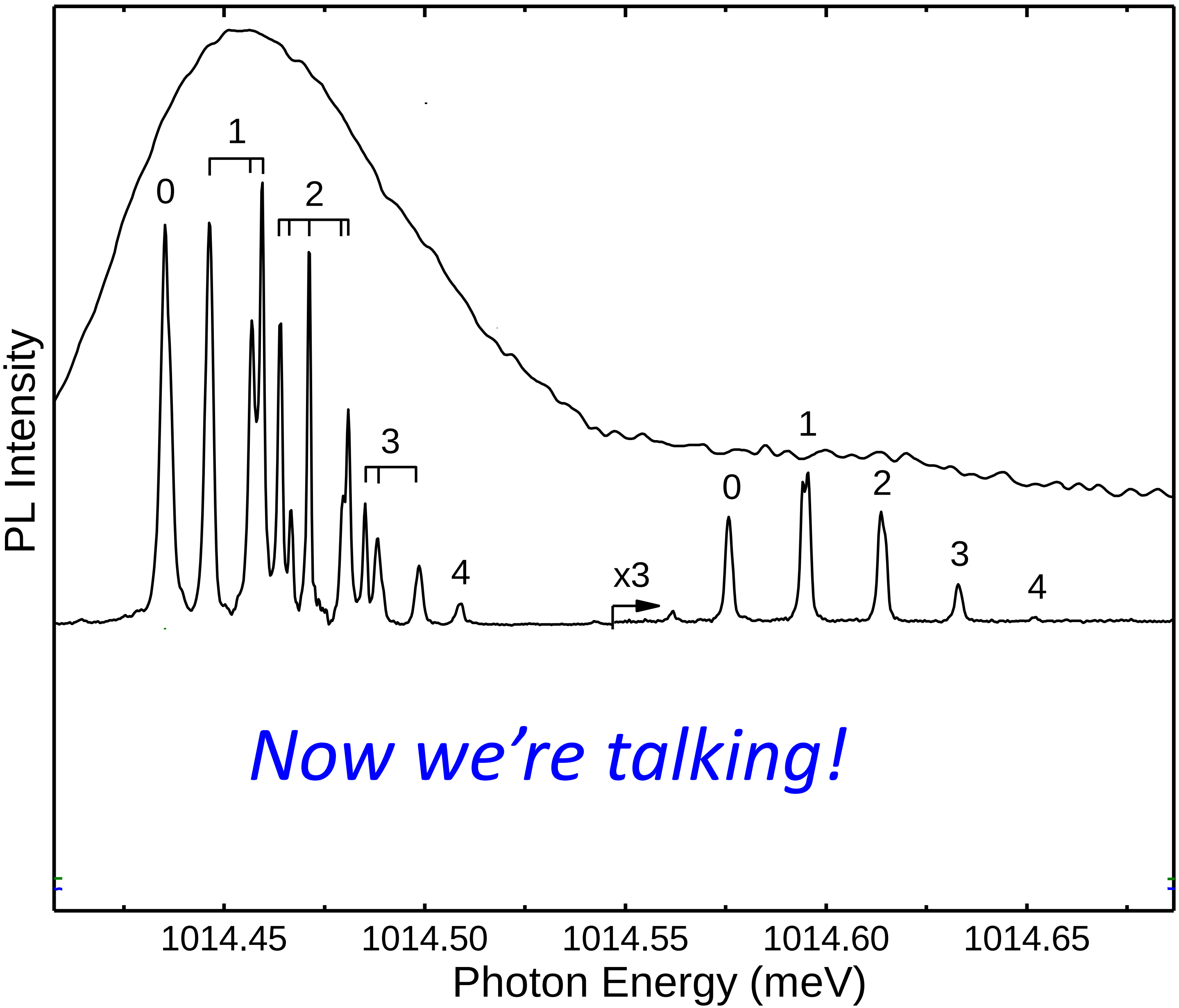
Simon Fraser University

CAP Congress, June 2019

My biases as a spectroscopist…



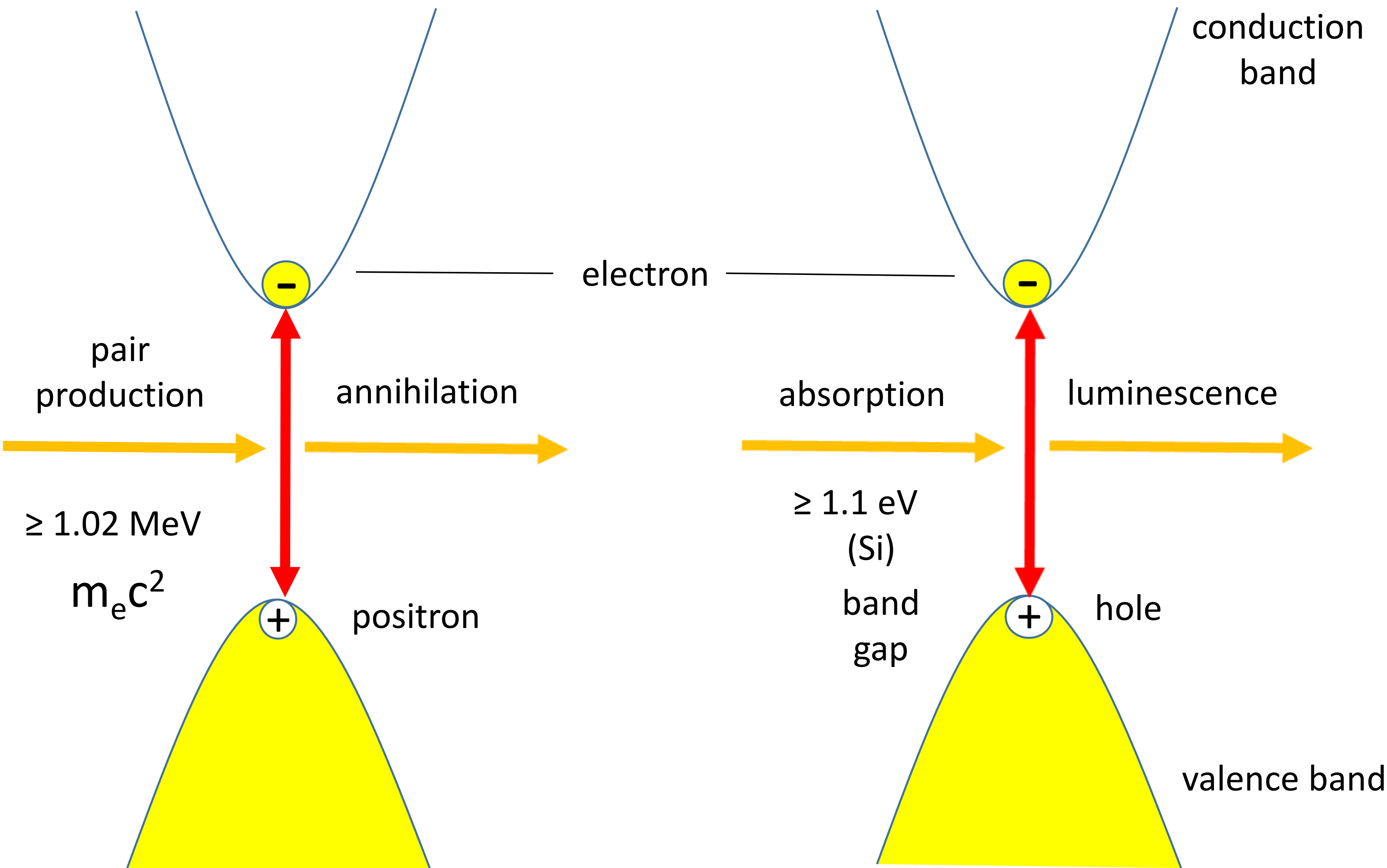
spectra of the same physical system!



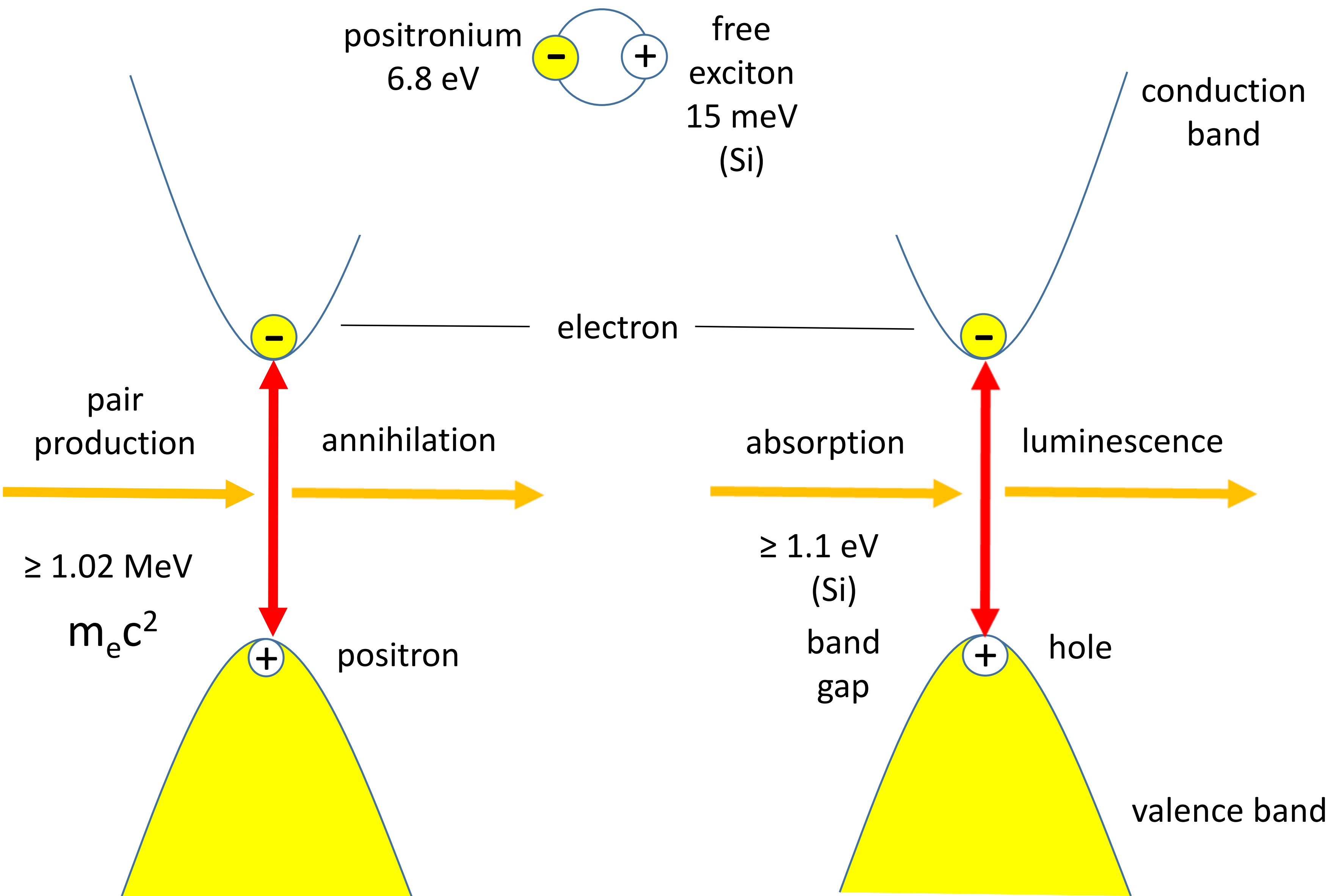
Now we're talking!

vacuum

semiconductor



vacuum semiconductor



The analogy has historical significance…

Volume 1, Number 12 PHYSICAL REVIEW LETTERS December 15, 1958

MOBILE AND IMMOBILE EFFECTIVE-MASS-PARTICLE COMPLEXES IN NONMETALLIC SOLIDS

Murray A. Lampert

charged donor bound exciton

Overcharged donor (D^-)

trion

biexciton

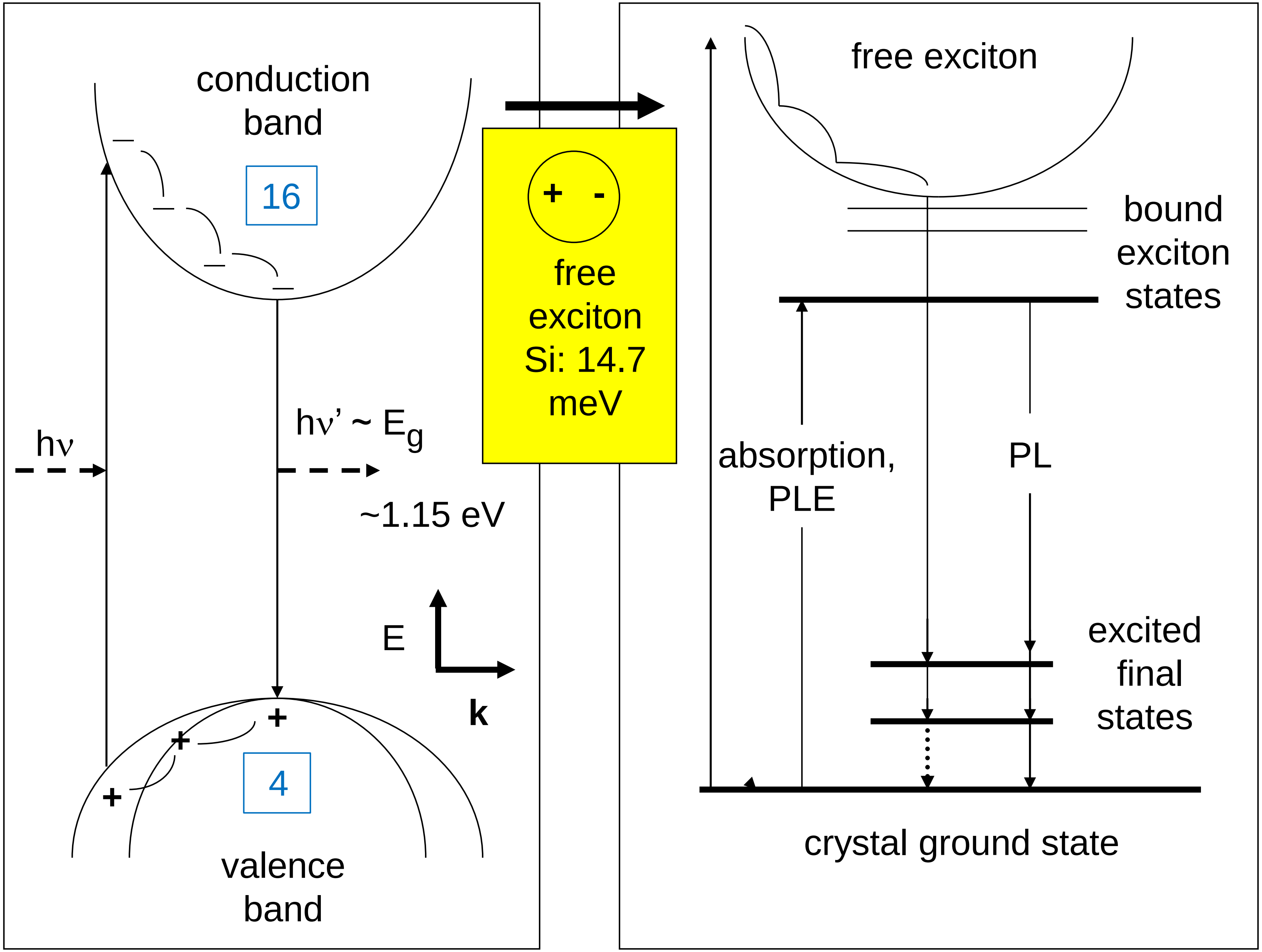
Donor bound exciton (D^0X)

Complex	m_h/m_e	Analog	D_0	Average separations
A: $\oplus+-$	$>>1$	H_2^+	0.21	$r_{\oplus+}\simeq 2$
	$<<1$	See text		
B: $\oplus--$		H^-	0.055	
C: $++-$	$>>1$	H_2^+	0.21	$r_{\oplus+}\simeq 2$
	1	$e^+e^+e^-$	0.0015[c]	
	$<<1$	H^-	$0.055m_h/m_e$	
D: $++--$	$>>1$	H_2	0.35	$r_{++}\simeq 1.4$
	1	$e^+e^+e^-e^-$	0.010[d]	$r_{++}=r_{--}\simeq 8.5$[d] $r_{+-}\simeq 5.7$
	$<<1$	H_2	$0.35m_h/m_e$	$r_{--}\simeq 1.4m_e/m_h$
E: $\oplus+--$	$>>1$	H_2	0.35	$r_{\oplus+}\simeq 1.4$
	1	H^-e^+	0.0050[e]	
	$<<1$	See text		

Volume 4, Number 7 PHYSICAL REVIEW LETTERS April 1, 1960

EXPERIMENTAL PROOF OF THE EXISTENCE OF A NEW ELECTRONIC COMPLEX IN SILICON

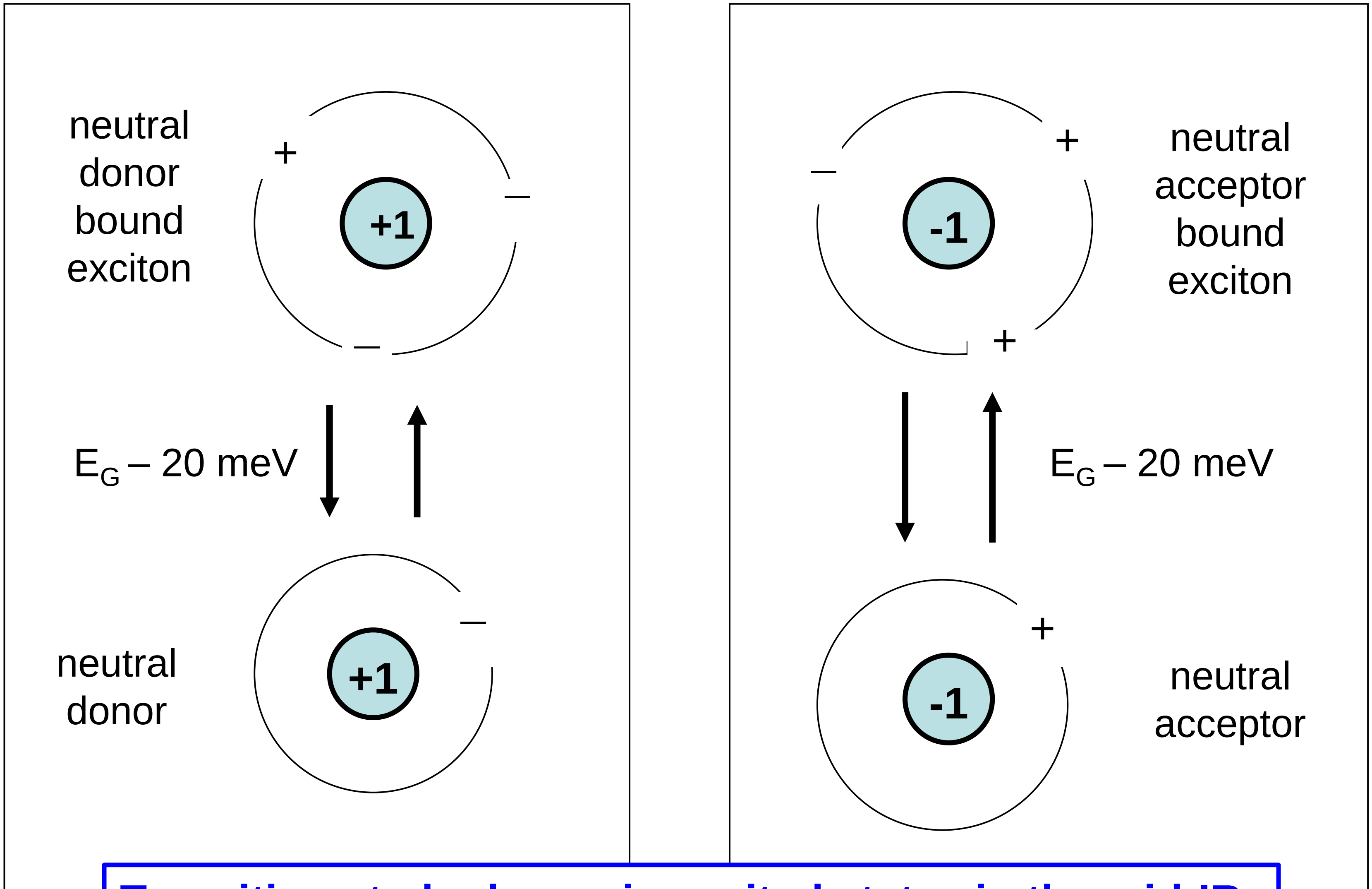
J. R. Haynes



conduction band
16
hν
hν' ~ E_g
~1.15 eV
E
k
4
valence band
+ -
free exciton
Si: 14.7 meV
free exciton
bound exciton states
absorption, PLE
PL
excited final states
crystal ground state

Neutral donors, neutral acceptors, and their bound excitons

(D^0) (A^0) (D^0X, A^0X)



Transitions to hydrogenic excited states in the mid-IR

a diversion before getting to ^{28}Si, related to the vacuum analogy…

Physics Letters A 42, 4 December 1972, Pages 189-190

Excitonic molecules: A possible new form of chemical bonding

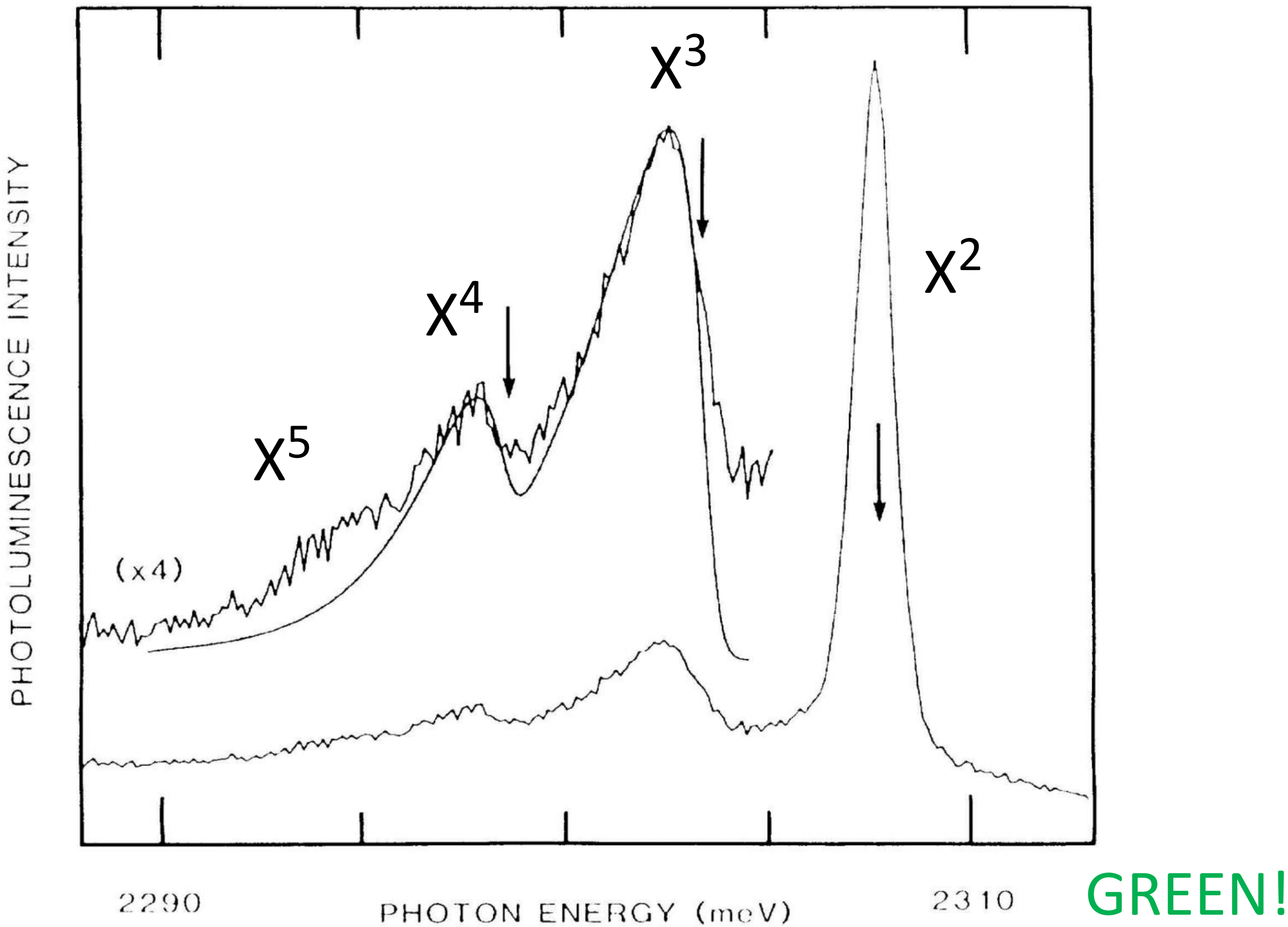
J. Shy-Yih Wang, C. Kittel

If a band edge has **N** equivalent minima in the Brillouin zone, it is possible consistent with the exclusion principle to place 2**N** identical electrons in the same molecular orbital. This theorem suggest the possible stability of exciton molecular complexes, $(exc)_8$ in Ge and $(exc)_{12}$ in Si.

beyond the vacuum – H_3, H_4, H_5 …. molecules

Discovery of Polyexcitons

A. G. Steele, W. G. McMullan, and M. L. W. Thewalt



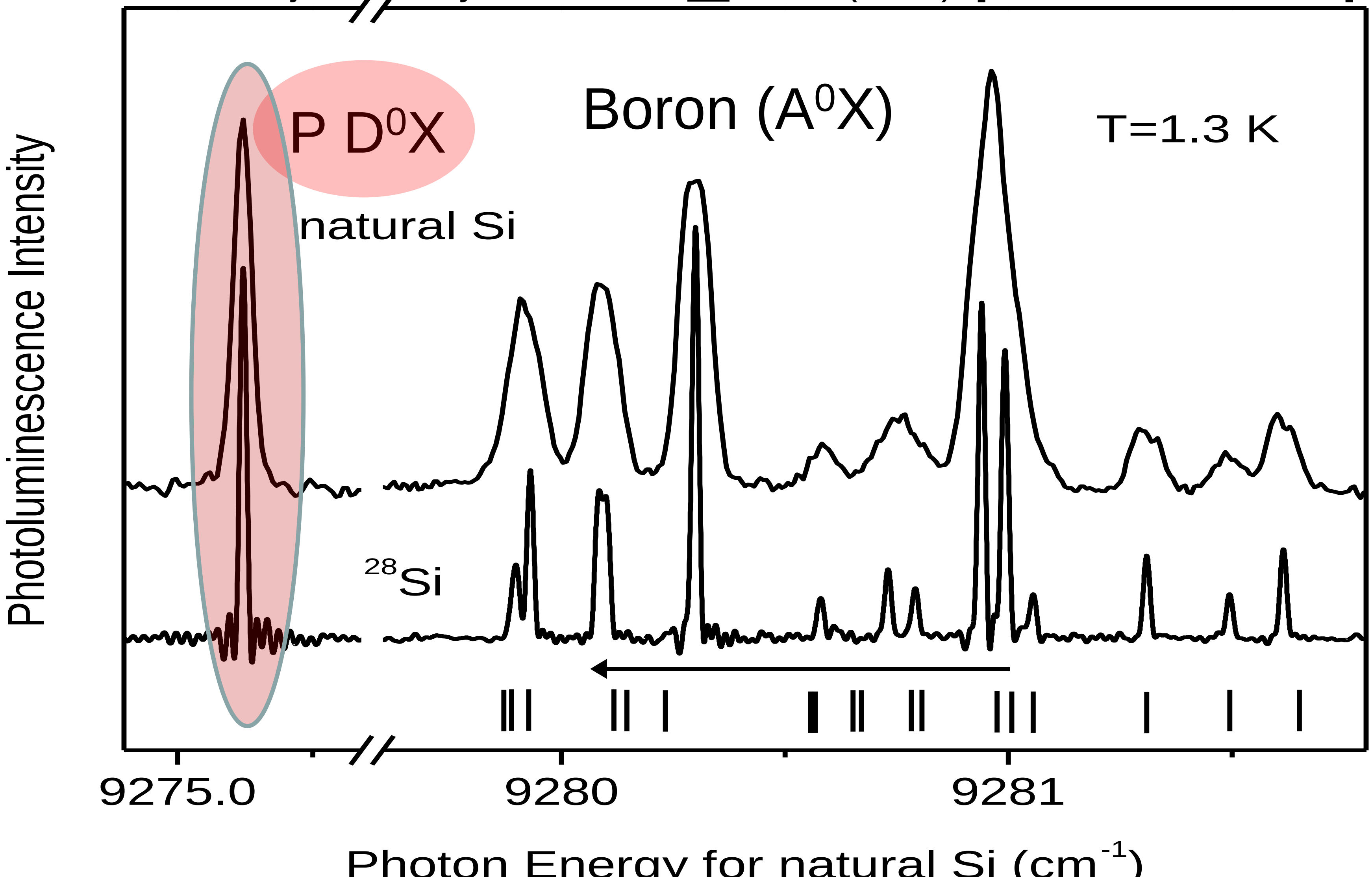
^{28}Si – the Avogadro Project

- isotope enrichment and chemical purification in Russia
- single crystal growth and project management in Germany
- spheres in Australia
- metrology around the world

The ~10 cm diameter spheres weigh ~ 1 Kg and are round to within 30 nm

Optical spectroscopy of ^{28}Si begins with a surprise (and a challenge)

D. Karaiskaj et al., Phys. Rev. Lett. 86, 6010 (2001) [FWHM < 0.005 cm^{-1}]



(8 cm^{-1} ~ 1 meV)

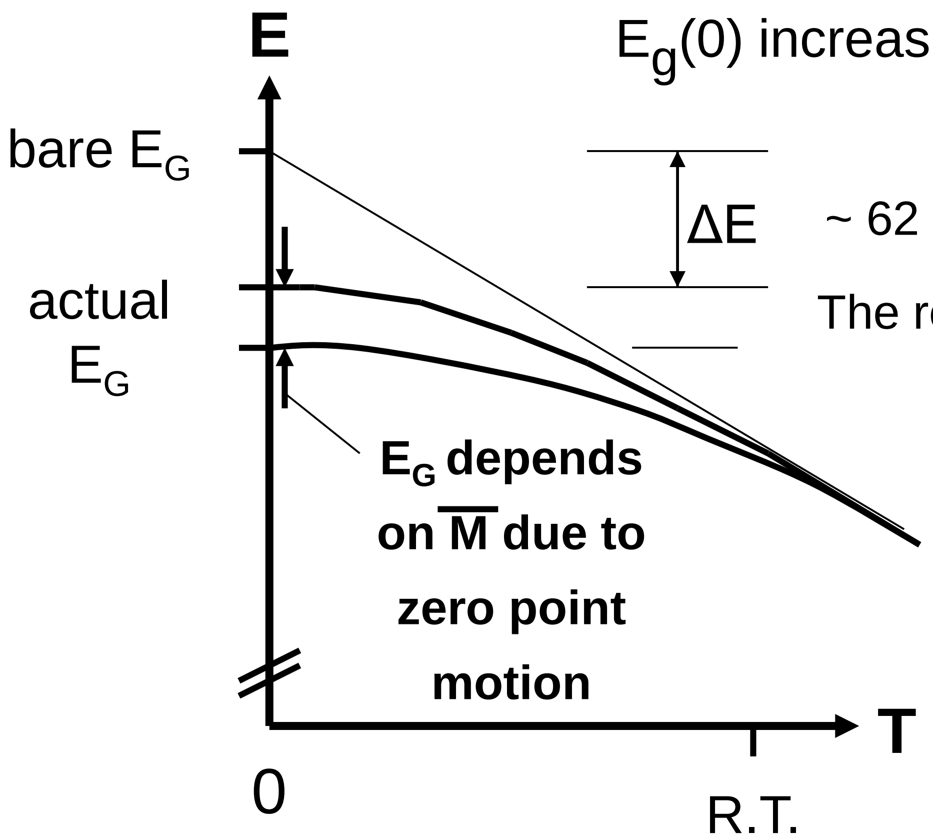
Natural Si: 92.2% ^{28}Si + 4.7% ^{29}Si + 3.1% ^{30}Si

$I = 0$ **$I = ½$** $I = 0$

Why does the isotopic composition affect electronic and optical properties?

→ the electron-phonon interaction

$E_g(0)$ increases by ~2 meV from ^{28}Si to ^{30}Si



~ 62 meV for ^{nat}Si

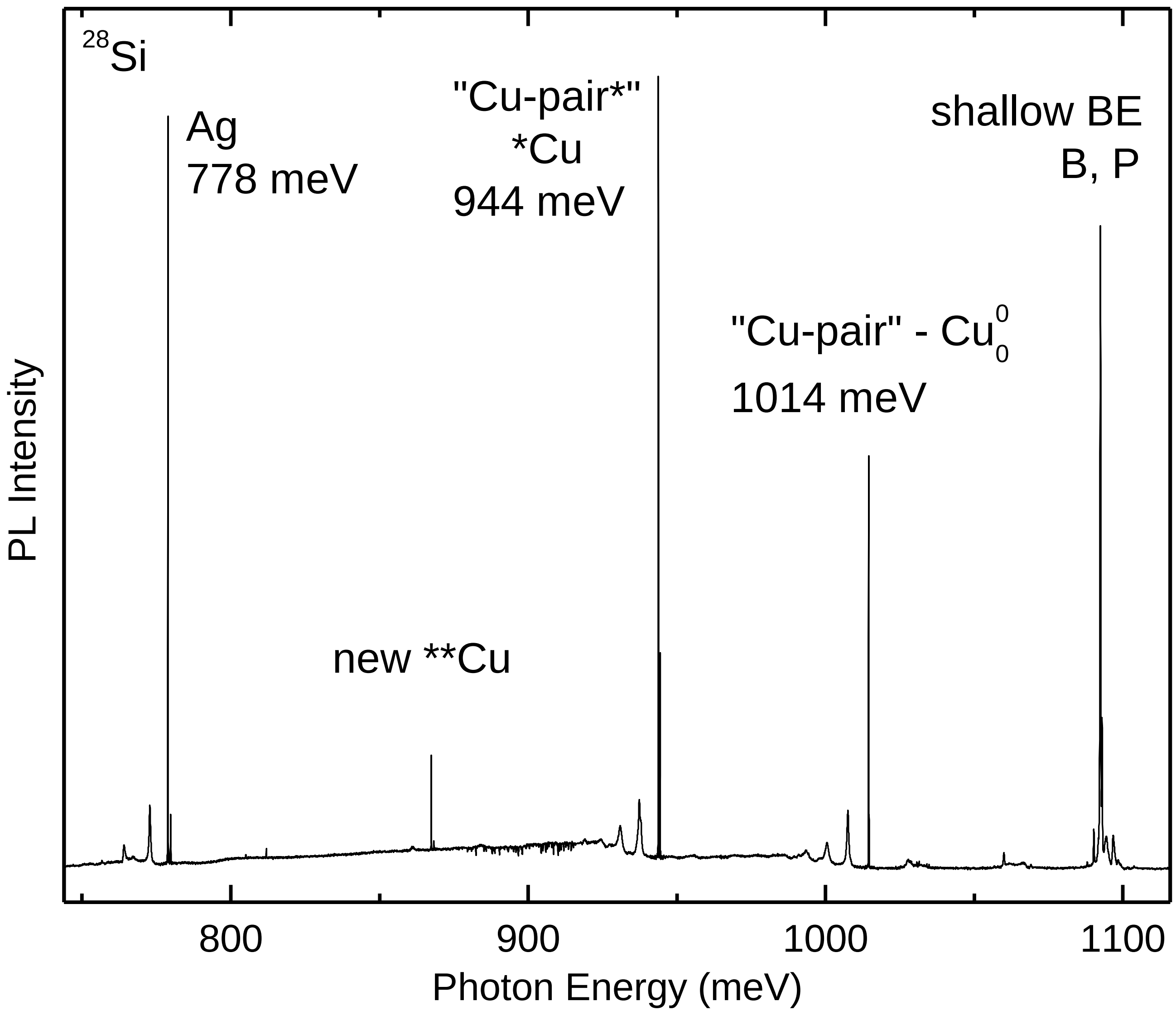
The renormalization goes as $\overline{M}^{-1/2}$

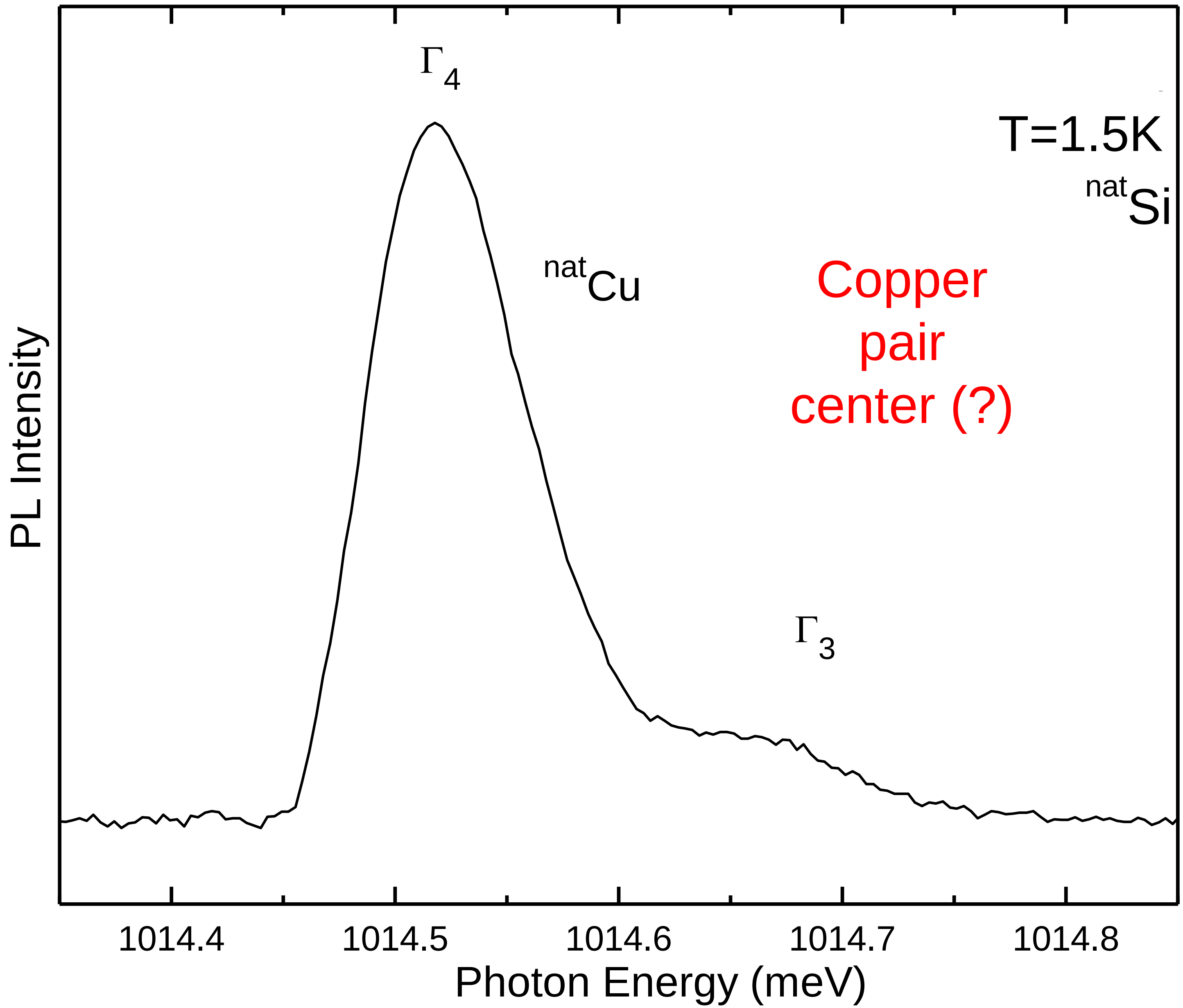
Cardona and Thewalt

Reviews of Modern Physics **77**, 1173 (2005)

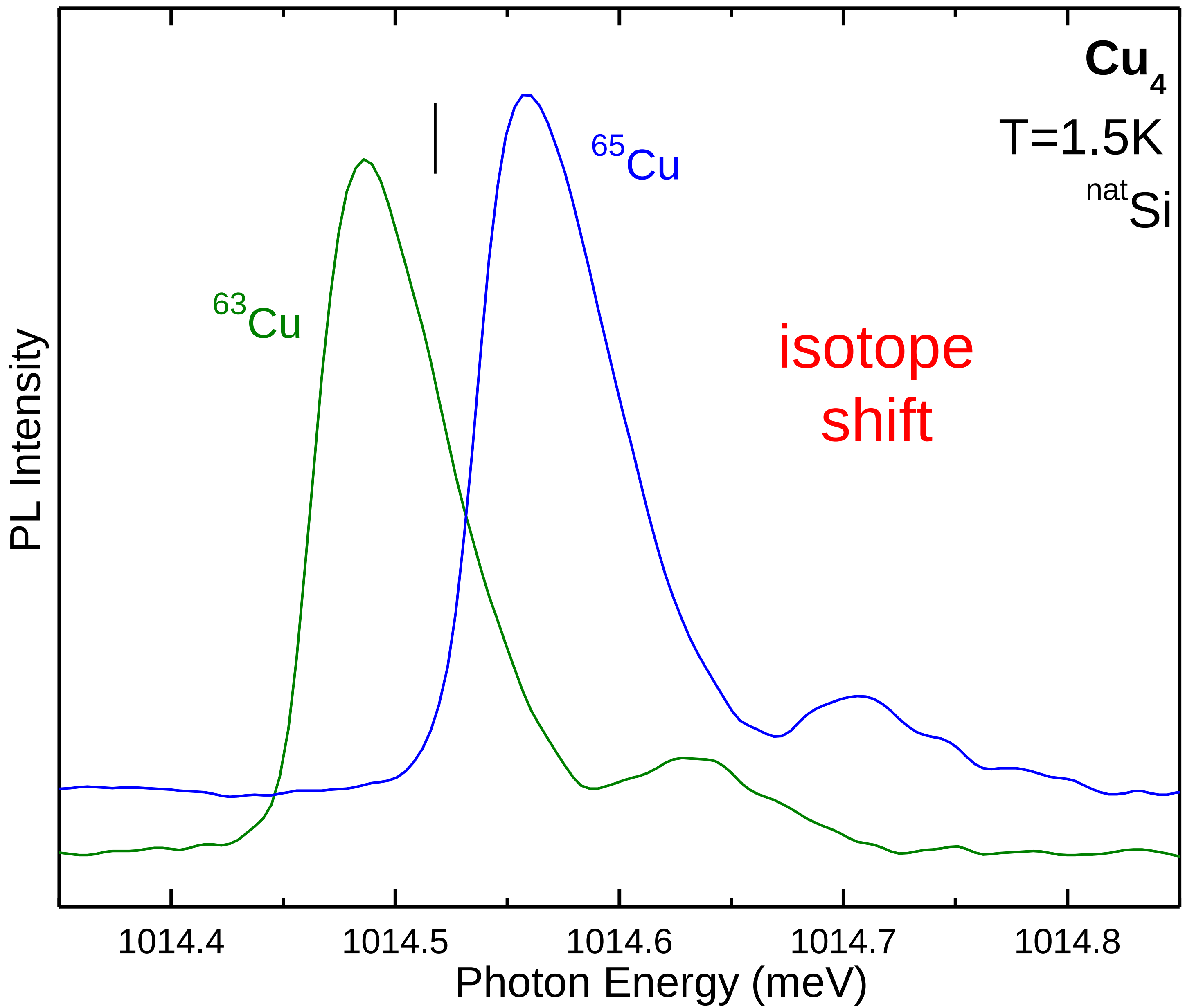
The ‘isotopic fingerprints’ of deep defect luminescence centers ^{28}Si

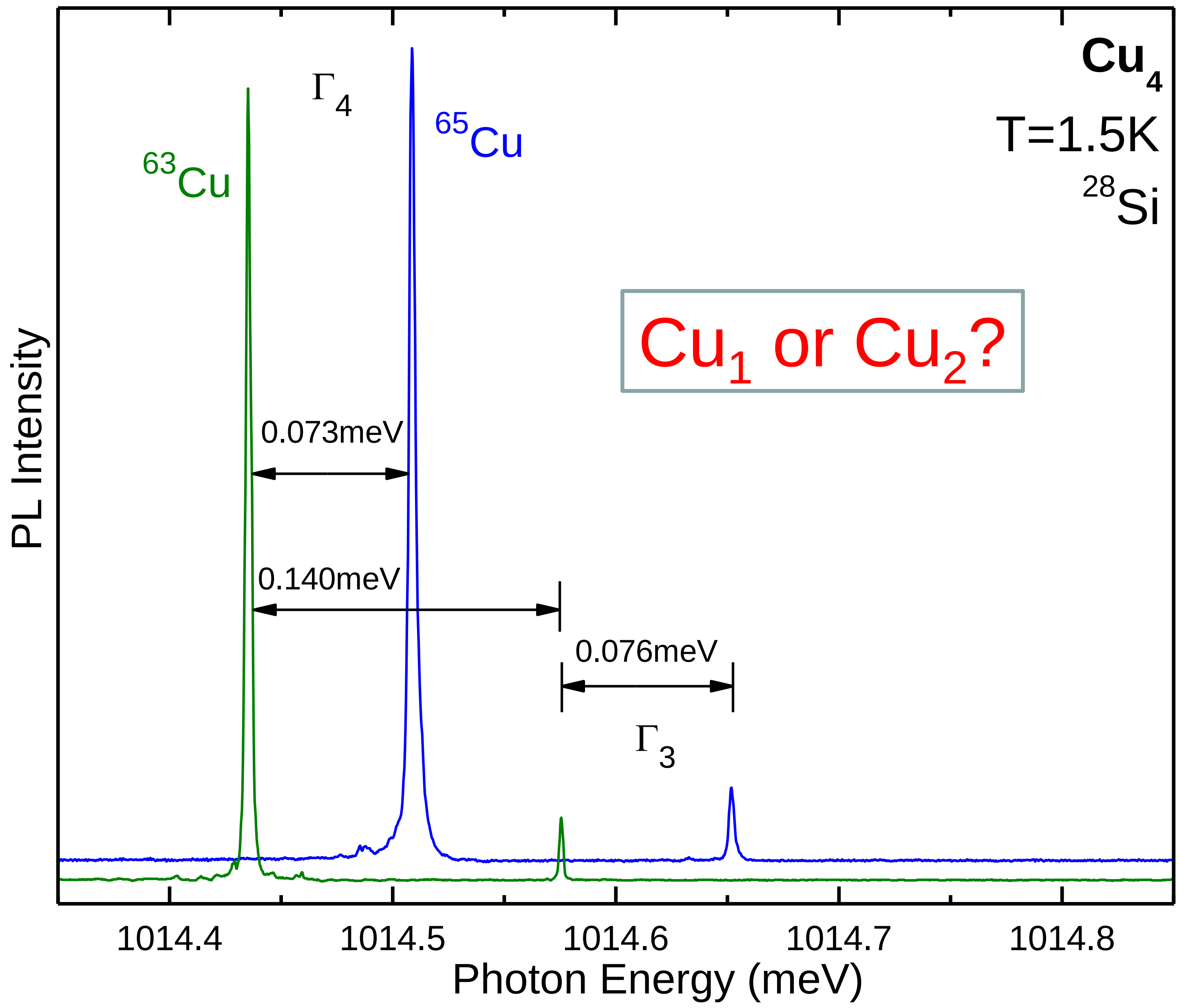
Some ‘well-known’ deep defect luminescence in Si containing Cu and Ag:
(these can have very strong PL – ISOELECTRONIC bound excitons)



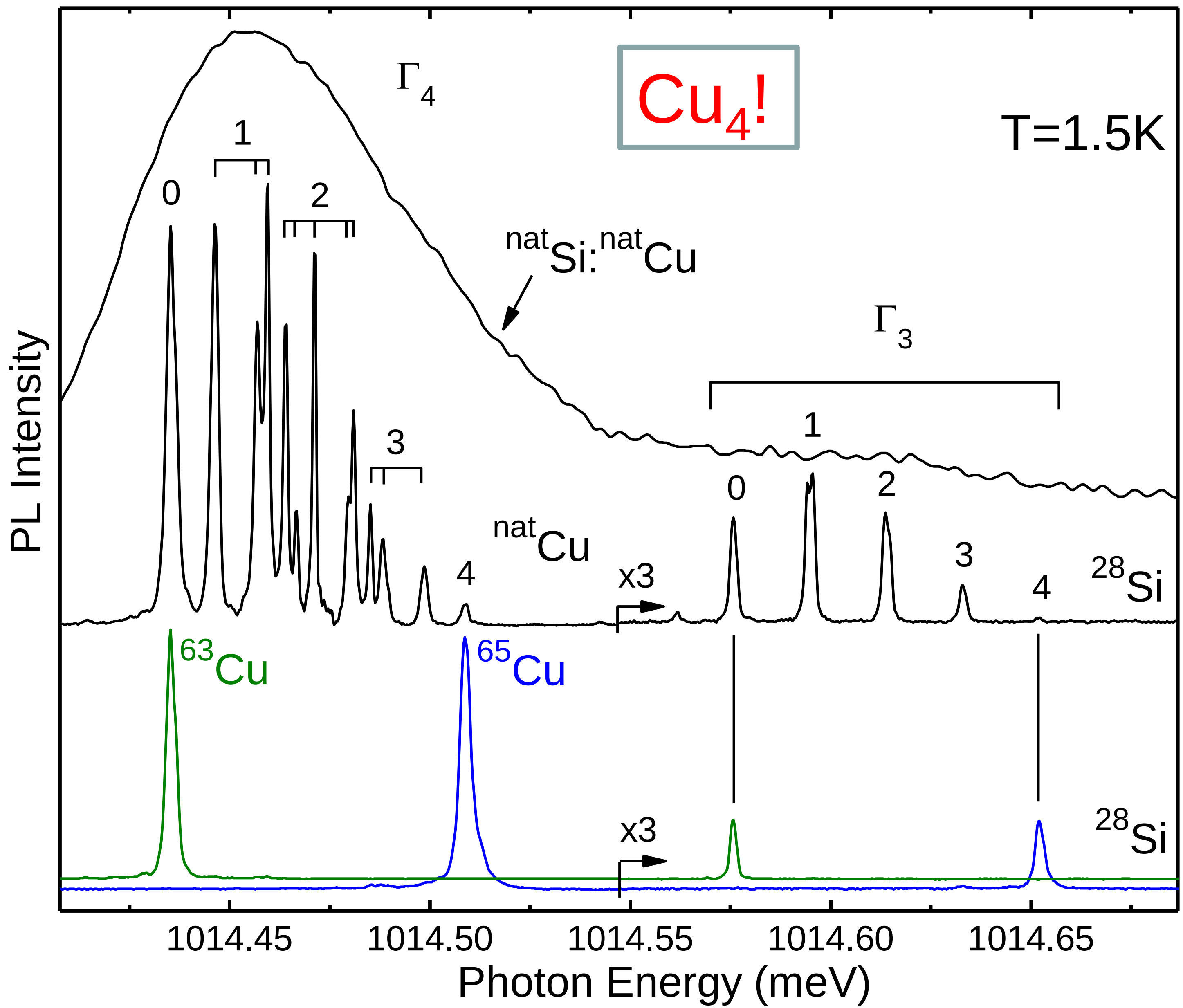


Γ4
T=1.5K
natSi
natCu
Copper
pair
center (?)
Γ3
PL Intensity
1014.4
1014.5
1014.6
1014.7
1014.8
Photon Energy (meV)


Cu4
T=1.5K
natSi
65Cu
63Cu
isotope
shift
PL Intensity
1014.4
1014.5
1014.6
1014.7
1014.8
Photon Energy (meV)



Cu4
T=1.5K
28Si
Γ4
63Cu
65Cu
Cu1 or Cu2?
0.073meV
0.140meV
0.076meV
Γ3
PL Intensity
1014.4
1014.5
1014.6
1014.7
1014.8
Photon Energy (meV)



Cu4!
T=1.5K
Γ4
Γ3
natSi:natCu
natCu
63Cu
65Cu
28Si
28Si
x3
x3
0
1
2
3
4
PL Intensity
1014.45
1014.50
1014.55
1014.60
1014.65
Photon Energy (meV)

Isotopic fingerprints:

None of these 'well known' centers is what it was thought to be!

'Cu-pair center'	1014 meV	Cu_4
'perturbed Cu-pair center'	944 meV	Ag_1Cu_3
'Ag_s center'	778 meV	Ag_4
'Fe center'	735 meV	$AuCu_3$
'Fe-B center'	1066 meV	$AuCu_4$

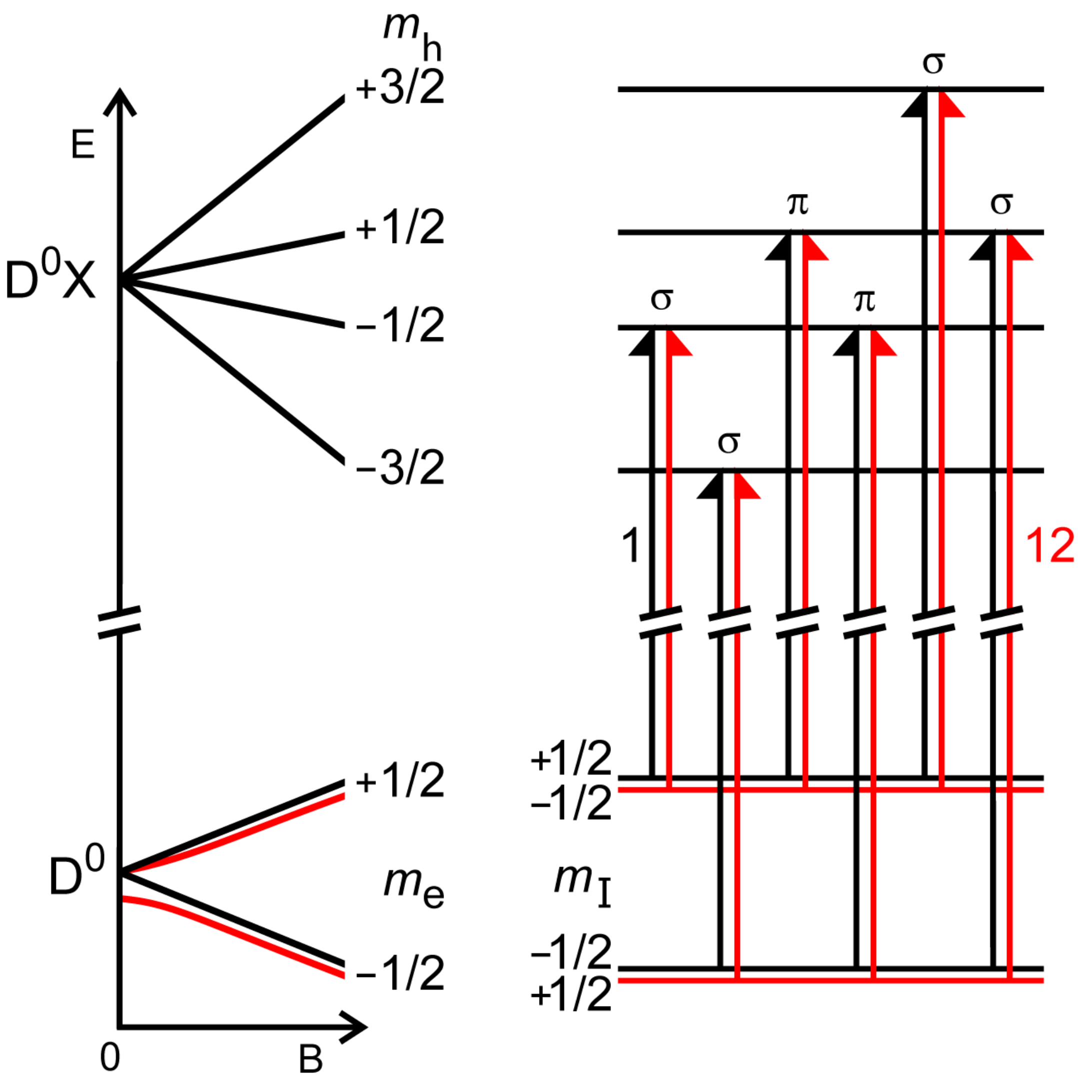
How many Au?

Also, many new deep luminescence centers have now been found containing 4 or 5 atoms chosen from: (Li, Cu, Au, Ag, Pt)

PRL 100, 177402 (2008), J. Appl. Phys. 110, 081301 (2011)

Difficulty with Au – only one stable isotope, ^{197}Au. Results using ^{195}Au (186 day half-life)

^{31}P Donor bound exciton Zeeman splitting

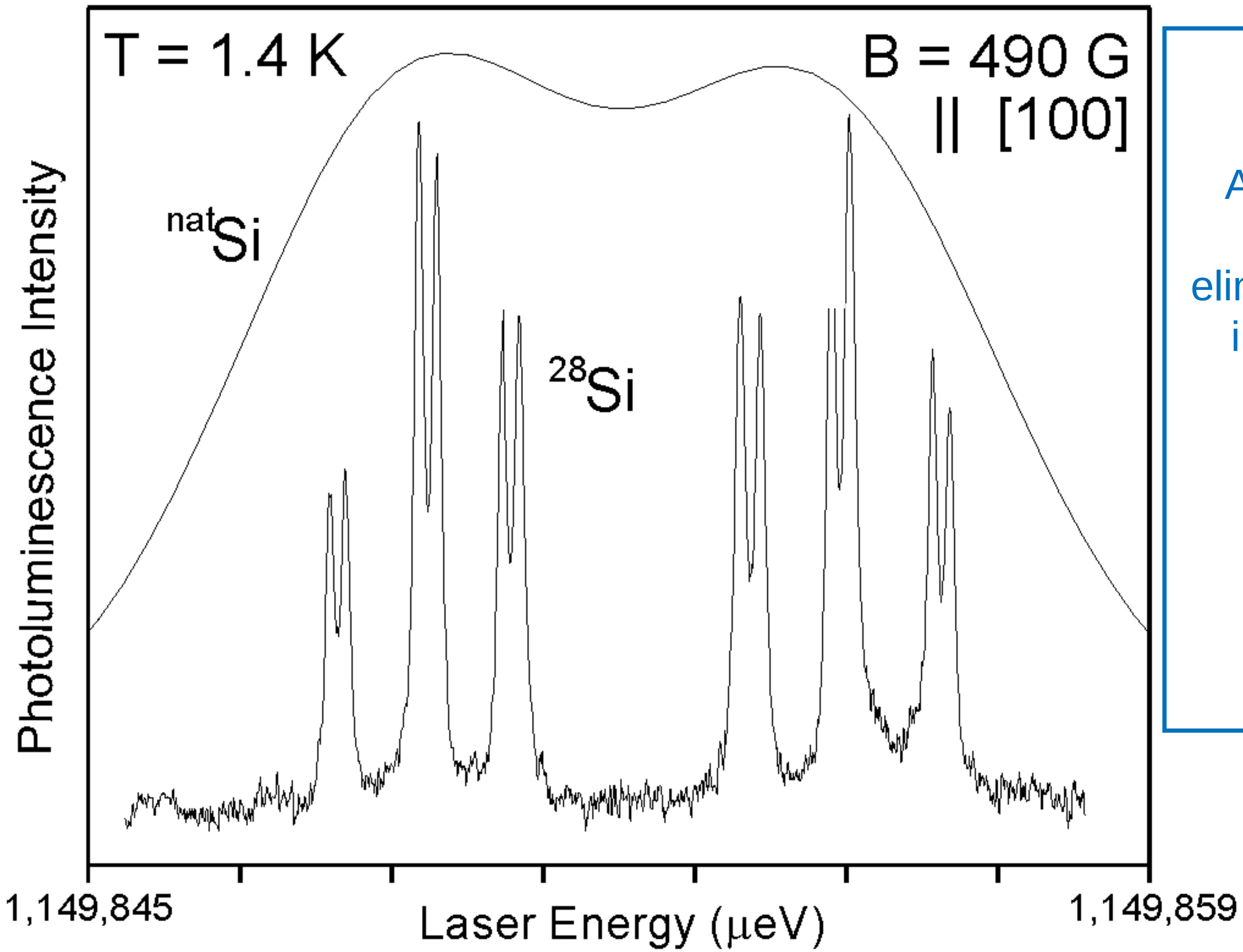


including hyperfine splitting, thought to be too small to observe in a bound exciton transition

The ^{31}P hyperfine splitting is 117 MHz (in a 273 THz transition)

The resolution challenge was solved by using absorption spectroscopy and single-frequency lasers, rather than PL

PRL 97, 227401 (2006) Nuclear and electron spin readout and initialization



^{28}Si:

A semiconductor vacuum – eliminates almost all inhomogeneous broadening mechanisms thought to be inherent to transitions in solid state systems

This enabled the measurement of record nuclear coherence times for ^{31}P in ^{28}Si

Science AAAS

Quantum Information Storage for over 180 s Using Donor Spins in a ^{28}Si "Semiconductor Vacuum"
M. Steger *et al.*
Science **336**, 1280 (2012);
DOI: 10.1126/science.1217635

Science AAAS

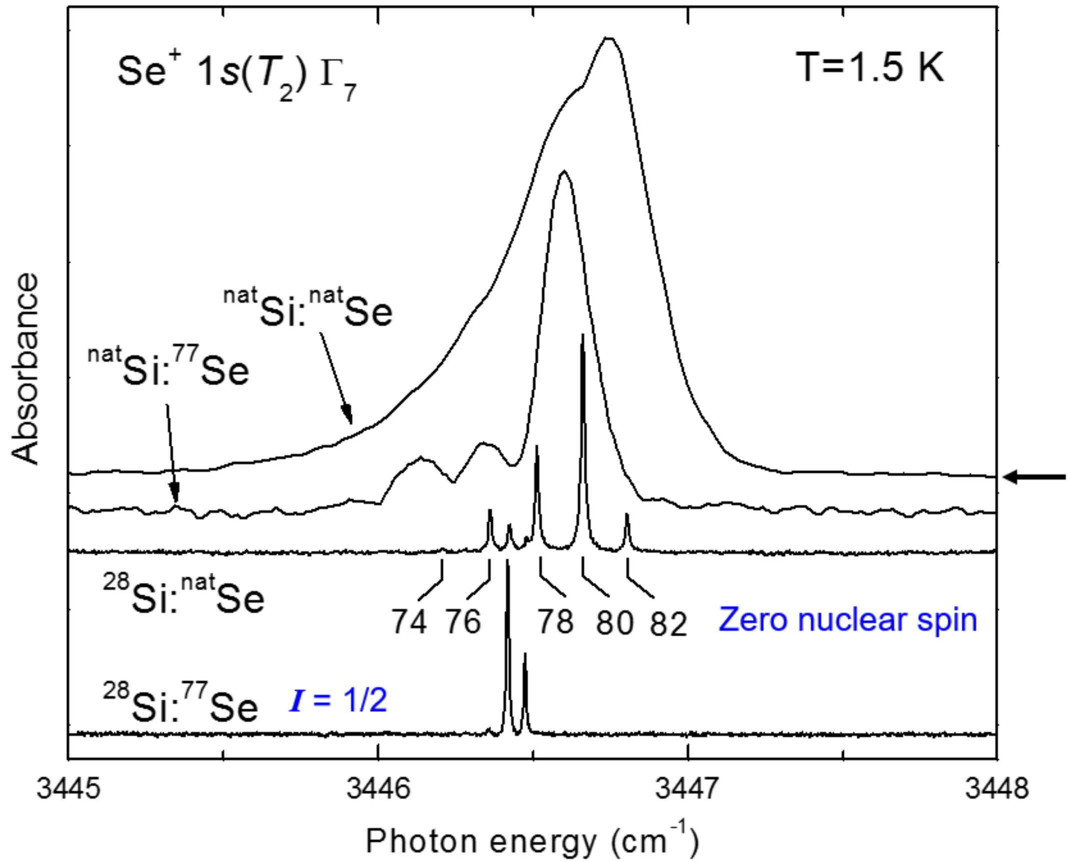
Room-Temperature Quantum Bit Storage Exceeding 39 Minutes Using Ionized Donors in Silicon-28
Kamyar Saeedi *et al.*
Science **342**, 830 (2013);
DOI: 10.1126/science.1239584

The electron and nuclear spins of donors in ^{28}Si are recognized as excellent qubit candidates, and compatibility with Si technology is a huge plus…

BUT – how do we perform operations between these qubits, or move the quantum information around?

Another possible qubit in silicon…

Deep Double Donor Absorption (Phys. Rev. B **80**, 115204 (2009))



Pajot et al. PRB 69, 085210, (2004)

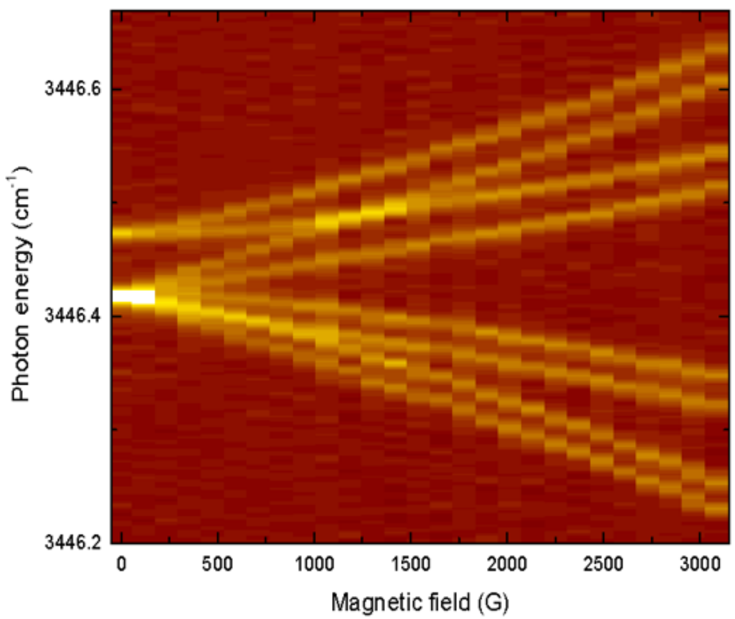
Chalcogens in Si are analogues of the He atom (2 electrons)

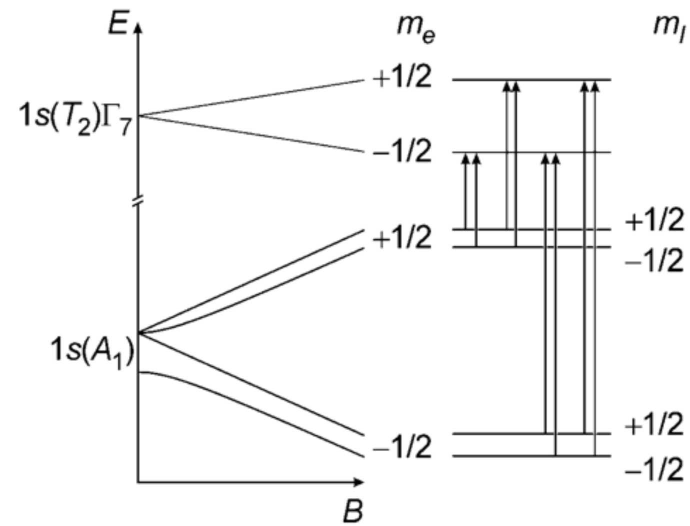
Only ^{77}Se has a nonzero nuclear spin and a hyperfine splitting

A different optical handle on electron/nuclear spin qubits in ^{28}Si

$^{77}Se^{+}$ has a large hyperfine splitting,
long nuclear spin coherence time, >2 sec

1.66 GHz

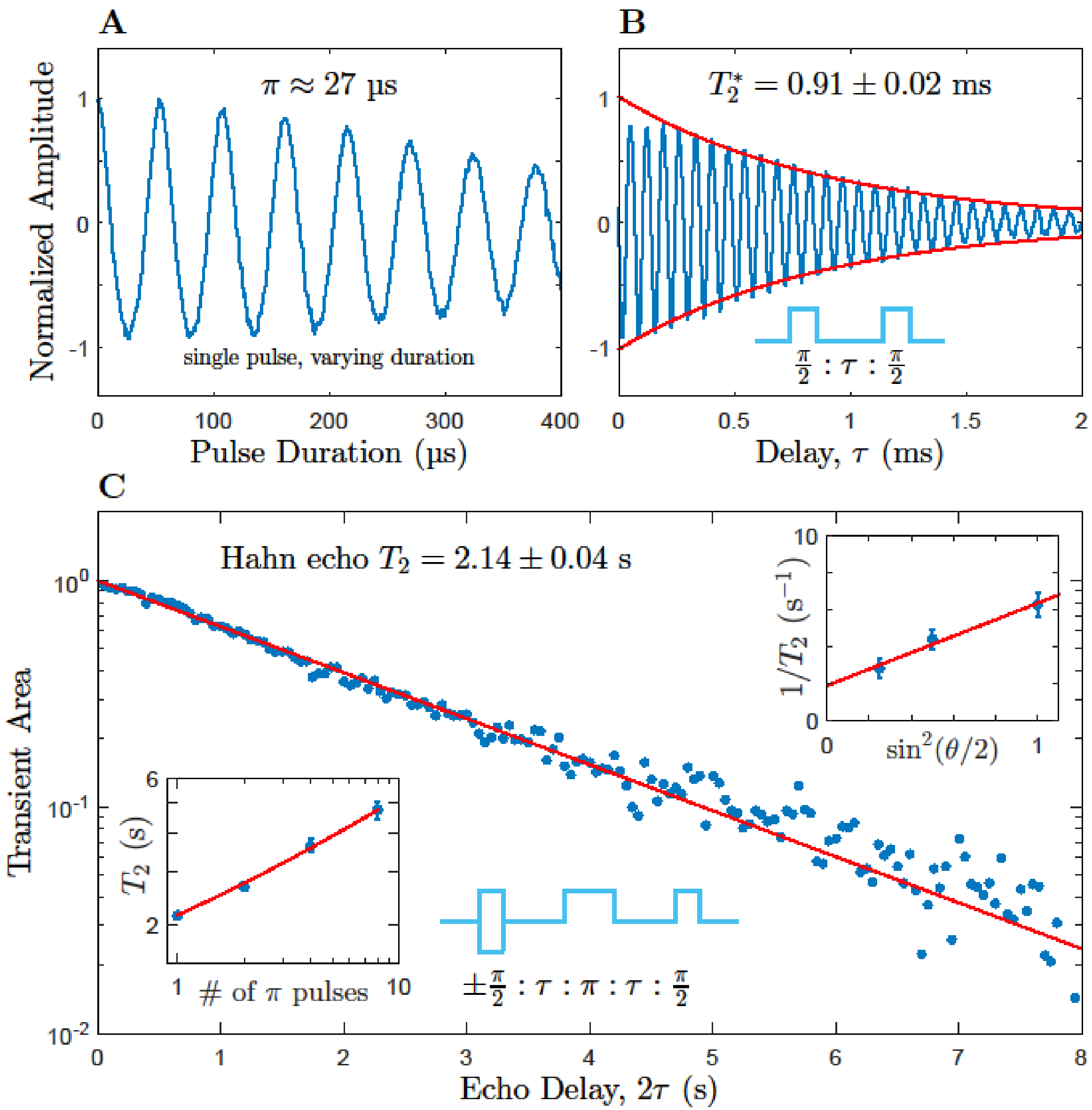




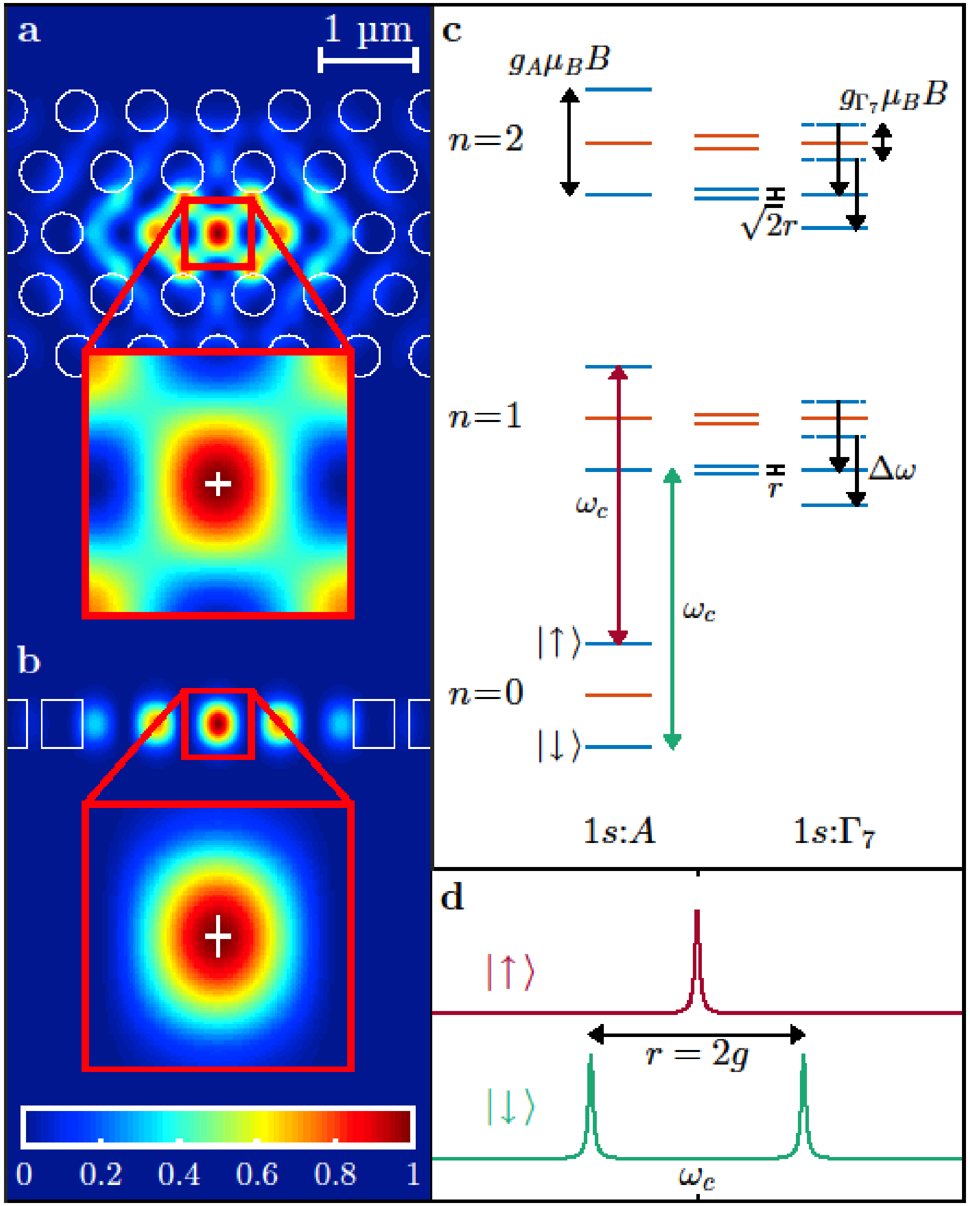
Chalcogens in Si may have advantages as qubits…..

There is still the problem of how to perform operations between qubits, and move quantum information around

K.J. Morse et al., Sci. Adv. 3, e1700930 (2017)
A. deAbreu et al., Phys Rev Appl 11, 044036 (2019)



Se transitions are strong compared to D^0X, use c-QED for spin/photon (Stephanie Simmons)

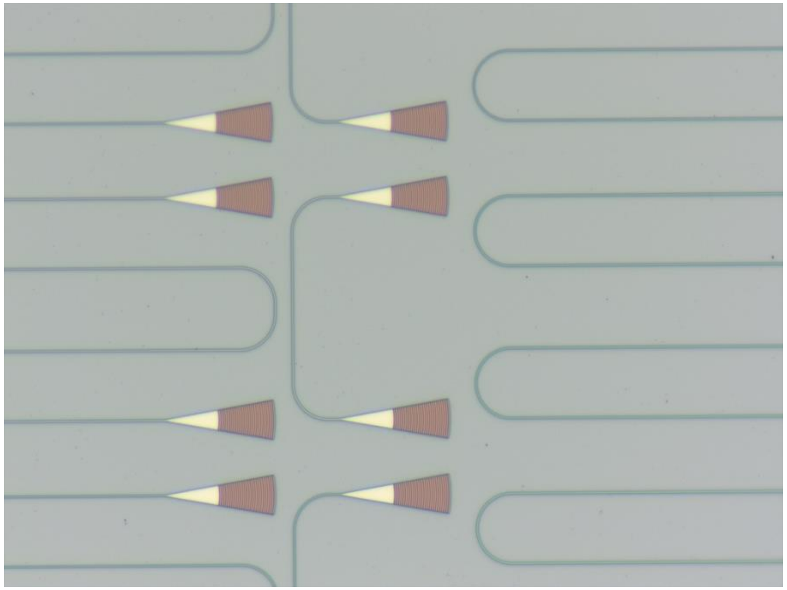


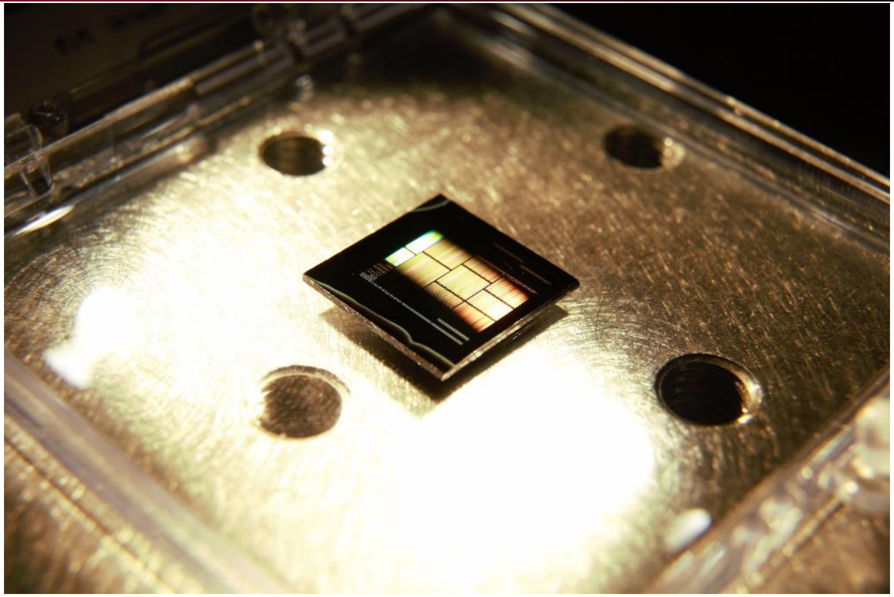
SILICON QUANTUM LEAP PROJECT

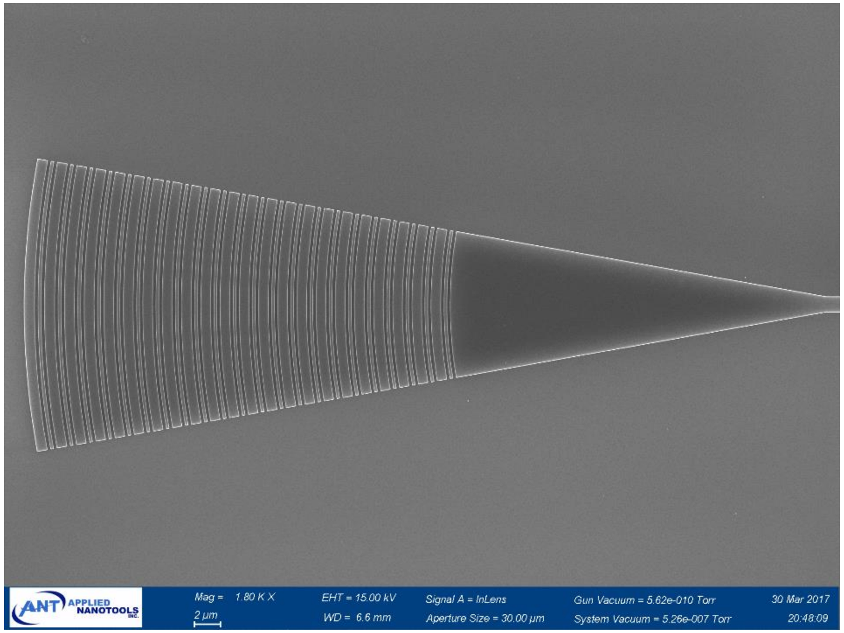
- Integrated silicon photonics is well-developed at ~1.5 μ (Lukas Chrostowski, UBC) High Q resonators at 1.5 μ
- Very high QE, low dark count integrated supercon. single photon detectors (Jeff Young, UBC)
- Strong coupling c-QED should be possible
- This would allow remote coupling, less need for precise donor placement
- Need to shift and test designs for 2.9 μm

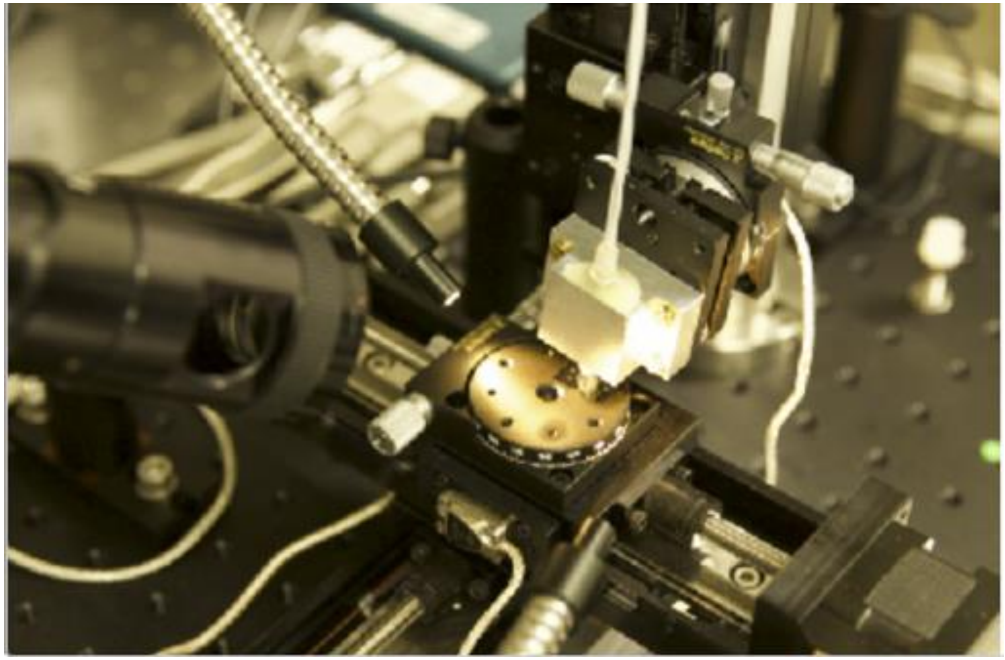
Working on 2.9 µ couplers, waveguides, resonators

SFU









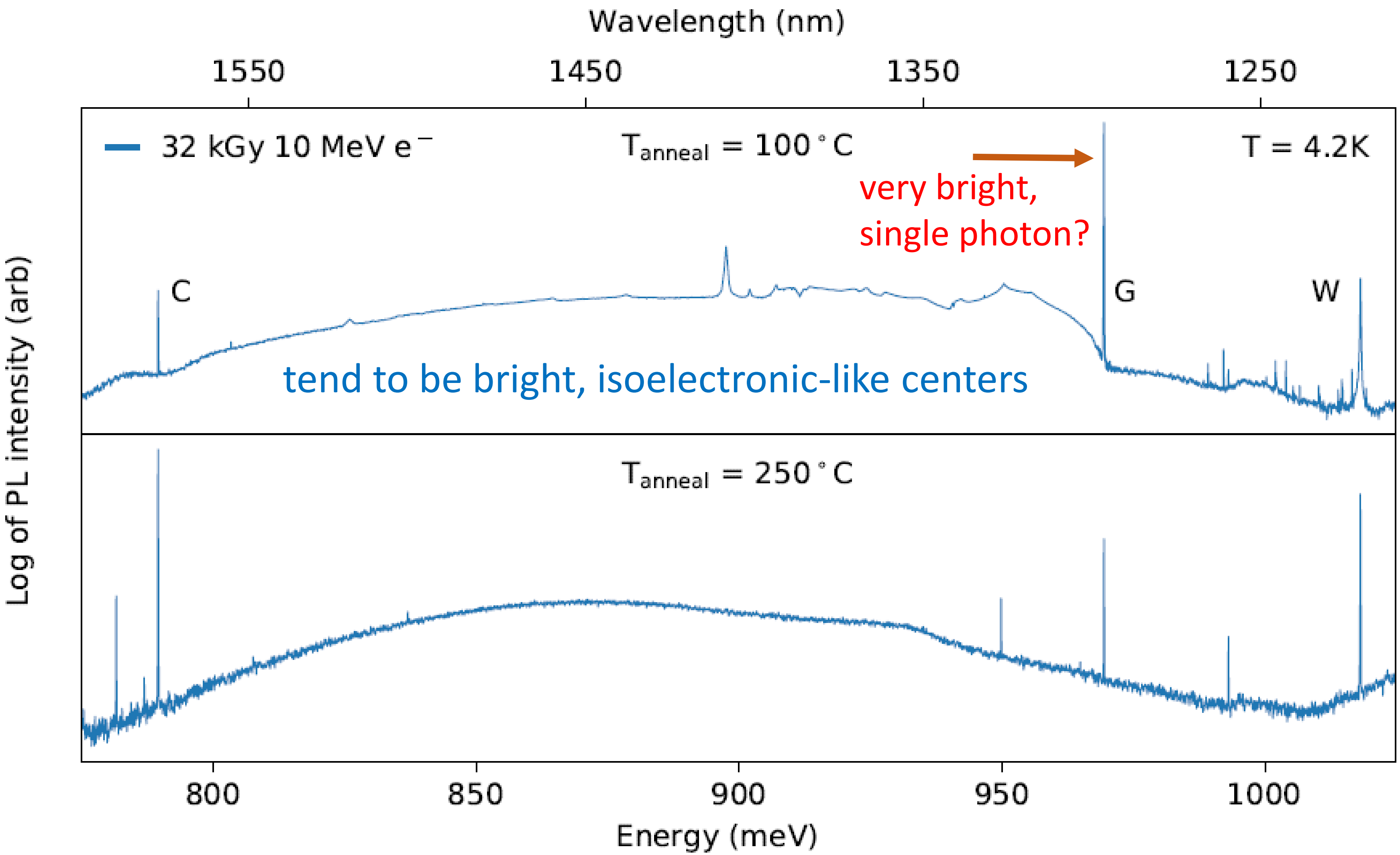
Admittedly, working at 2.9 microns has its drawbacks:

- Fibers
- Optics
- Sources
- Single photon detectors
- Room temp black body
- Extending silicon photonics

Radiation damage centers (color centers) as qubits

- Diamond – NV center
  - SiV center
- SiC – divacancy and other damage centers
  - cheaper than diamond, wafers available, but…
- Si – radiation damage centers studied for over 50 years
  - many are in the 1.3 to 1.55 μ telecom bands
  - almost no effort to examine them as qubits, some recent work on possibility of single-photon emitters
- **^{28}Si – let's reexamine some of these Si centers!**

Some very well known centres (10 MeV e⁻ damage)
C. Chartrand et al., Phys Rev B 98, 195201 (2018)



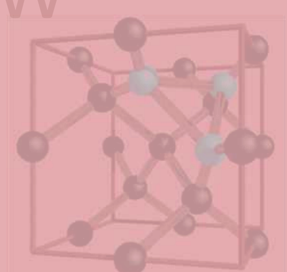
High resolution photoluminescence

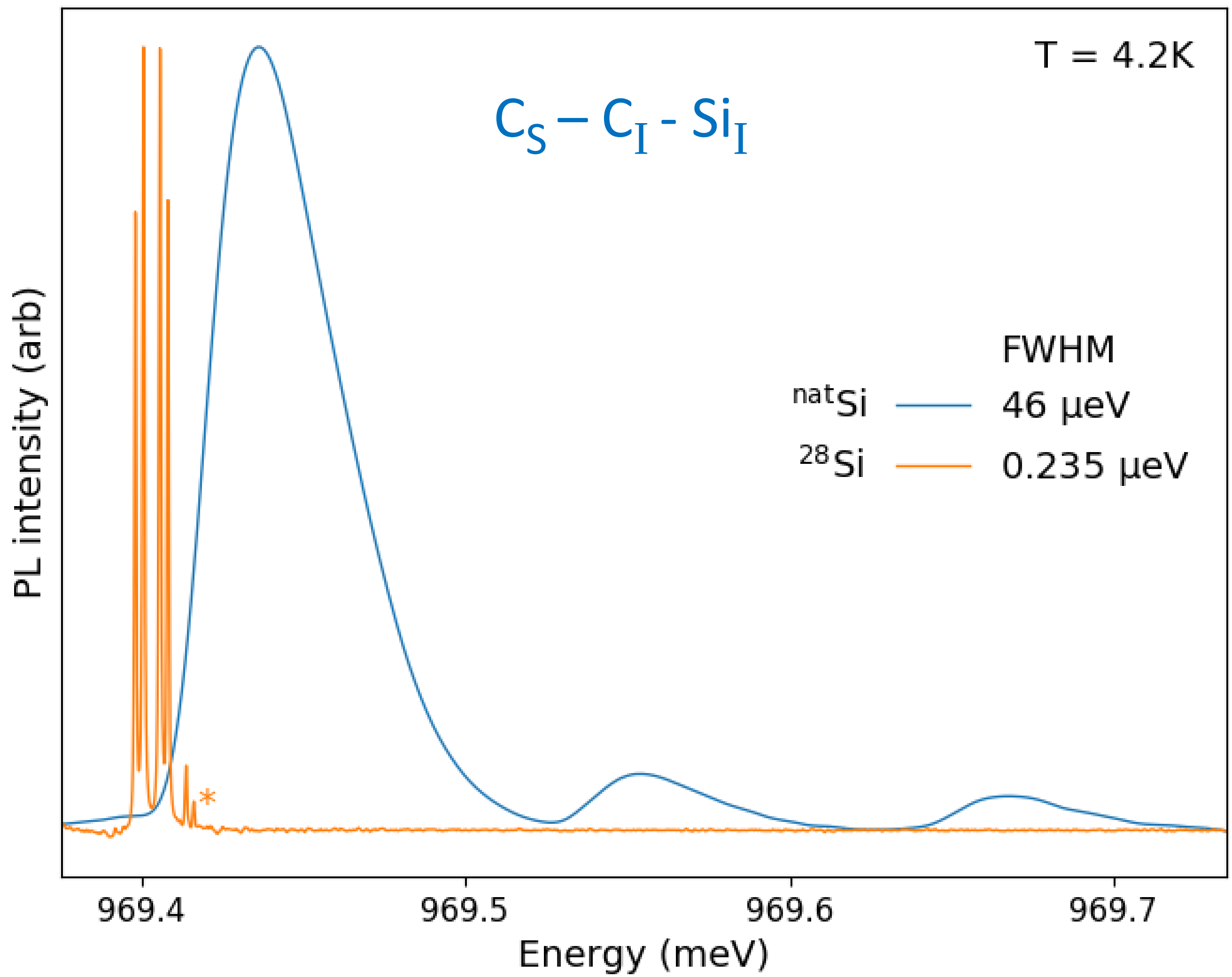
C

G

C. Chartrand

W





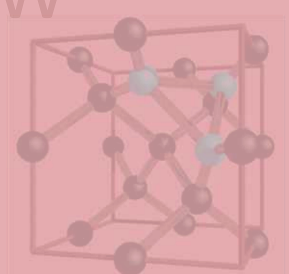
Absorption too!

C

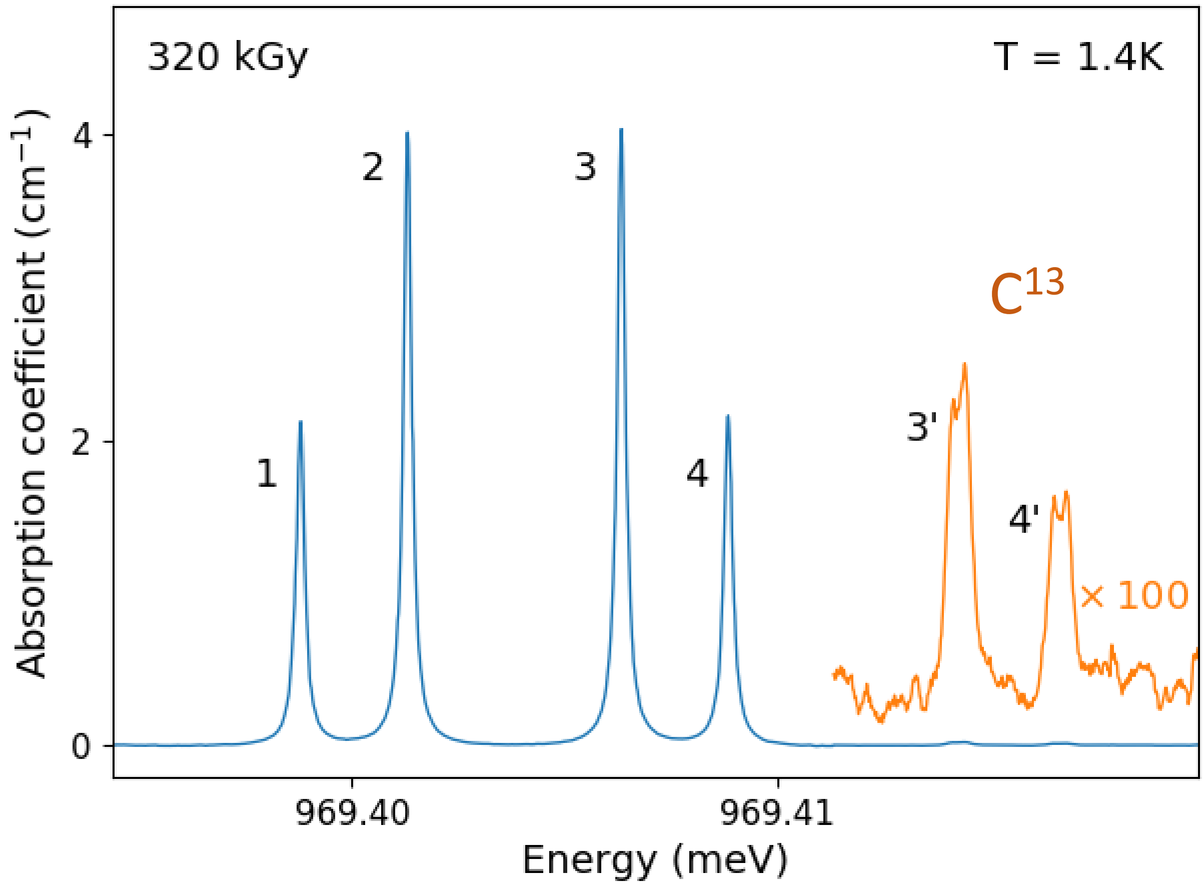
G

C. Chartrand

W



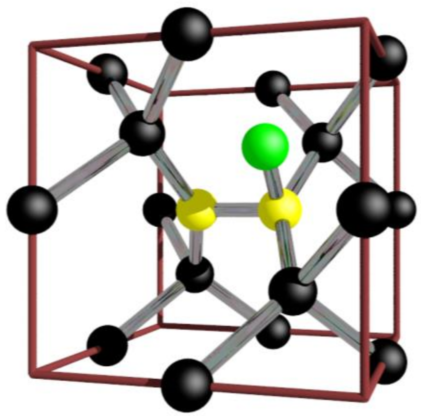
NOT a single line!
Origin of the fine structure?



Zero Zeeman splitting

Not a qubit candidate (neither is C or W)

T center (bare center has e^- spin ½)



C. Chartrand

Irradiation → Anneal

320 kGy   440C

	Se	T centre
Energy (nm)	2902	1326
Linewidth (MHz)	~30	~30
ZPL fraction (%)	16(1)	24(2)
Radiative lifetime (us)	0.90(7)	7(1)
Dipole moment (D)	1.98(8)	0.27(3)
Efficiency (%)	0.80(9)	14(4)
T_1 (s)	14400	> 30
T_2 (s)	2.14(4)	1.1(1)
cavity Q	1.5e4	7.4e4

Further T details: session W2-2, BLU 10011, 13:15

Thank you!

W1-9
ASB 109000
11:15
11:30

SQT

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