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Quantum color centers in diamond studied by emission channeling with short-lived isotopes (**EC-SLI**) and radiotracer photoluminescence

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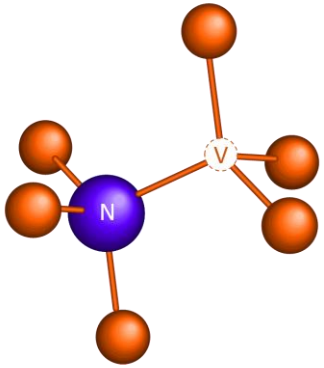
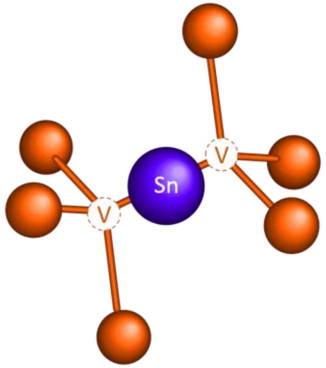
diamond color centers

- N*V*, Si*V*, Ge*V*, Sn*V* [1,2] and Pb*V* centers in diamond are intensively investigated
- two possible configurations for impurity-vacancy centers:

"full-vacancy", assumed for **N*V***





"split-vacancy" [3,4], assumed for **Si*V*, Ge*V*, Sn*V*, Pb*V***

- N*V* center: long coherence time but low efficiency in coherent photonic applications
- superior optical properties of the group-IV-vacancy centers are to a large extent a consequence of the D_{3d} inversion (mirror) symmetry
- so far, no direct ***structural*** evidence available that these configurations are actually formed
- emission channeling lattice location experiments are uniquely suited to study this problem

[1] S.D. Tchernij *et al.*, ACS Photonics 4 (2017) 2580
[2] T. Iwasaki *et al*, Phys. Rev. Lett. 119 (2017) 253601
[3] J.P. Goss *et al.*, Phys. Rev. Lett. 77 (1996) 3041
[4] J.P. Goss *et al.*, Phys. Rev. B. 72 (2005) 035214

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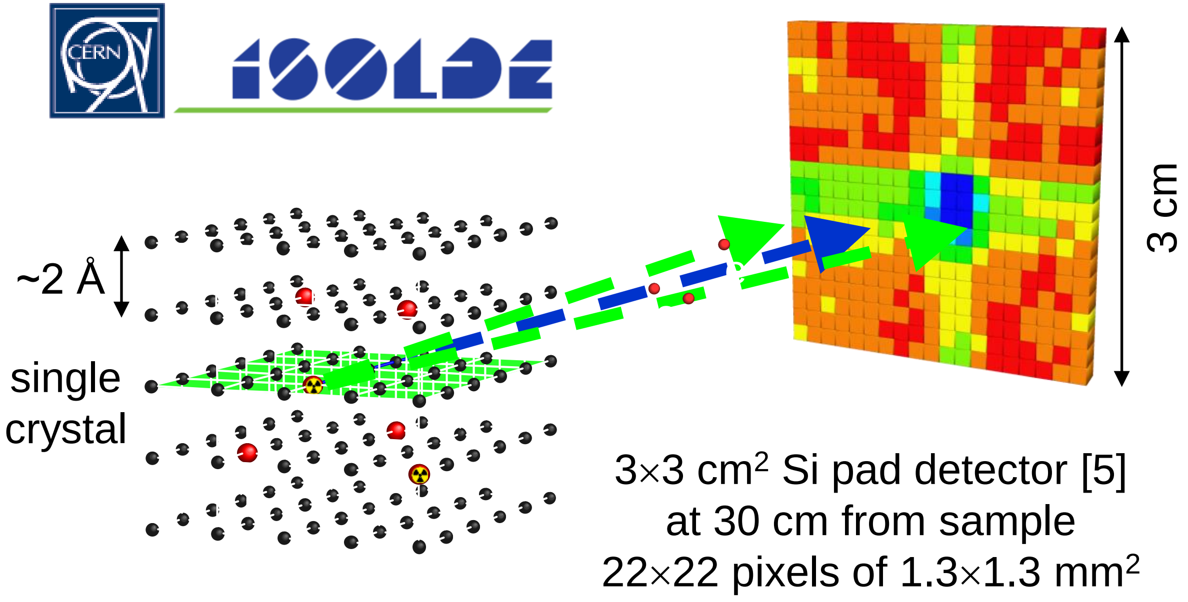
Emission Channeling with Short-Lived Isotopes (EC-SLI)

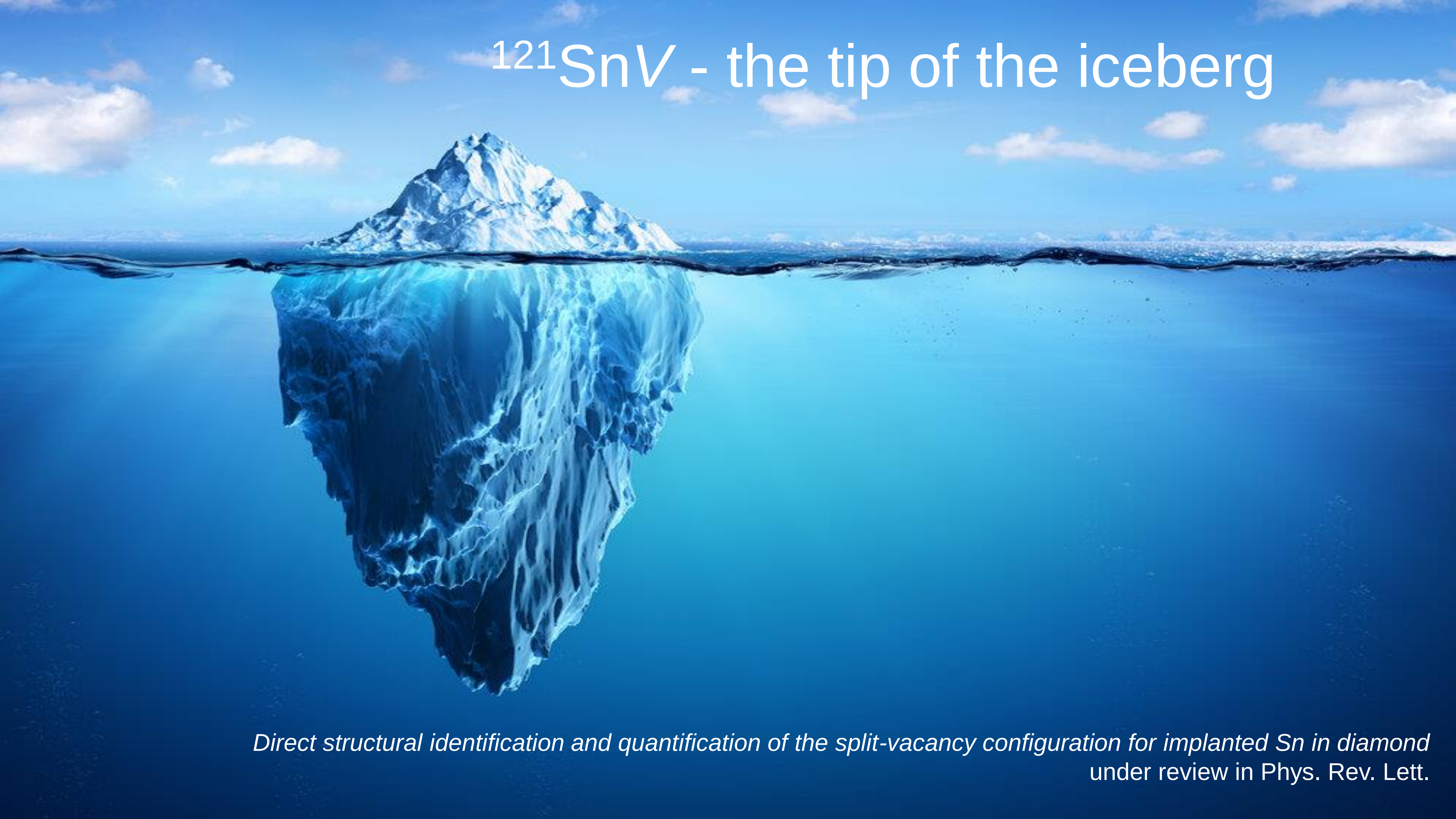
- radioactive probe atoms are produced at CERN's ISOLDE on-line isotope separator facility
- implanted (30-60 keV, 10^{11}-10^{12} cm^{-2}) into diamond at RT or elevated T (up to 900ºC)
- measured as-implanted and after thermal annealing up to 1200ºC
- position- and energy sensitive detector [5] is used to detect emission channeling [6] effects of β^- decay particles from the implanted probes in the vicinity of major crystallographic directions.
- angular dependent β^- emission patterns characterize the lattice site distribution of the emitter atoms.



combined with radiotracer PL @ISOLDE
for **unambiguous** correlation
between **structure** and **photonics**

[5] U. Wahl *et al.*, Nucl. Instr. Meth. A 524 (2004) 245
[6] H. Hofsäss, G. Lindner, Phys. Rep. 201 (1991) 121

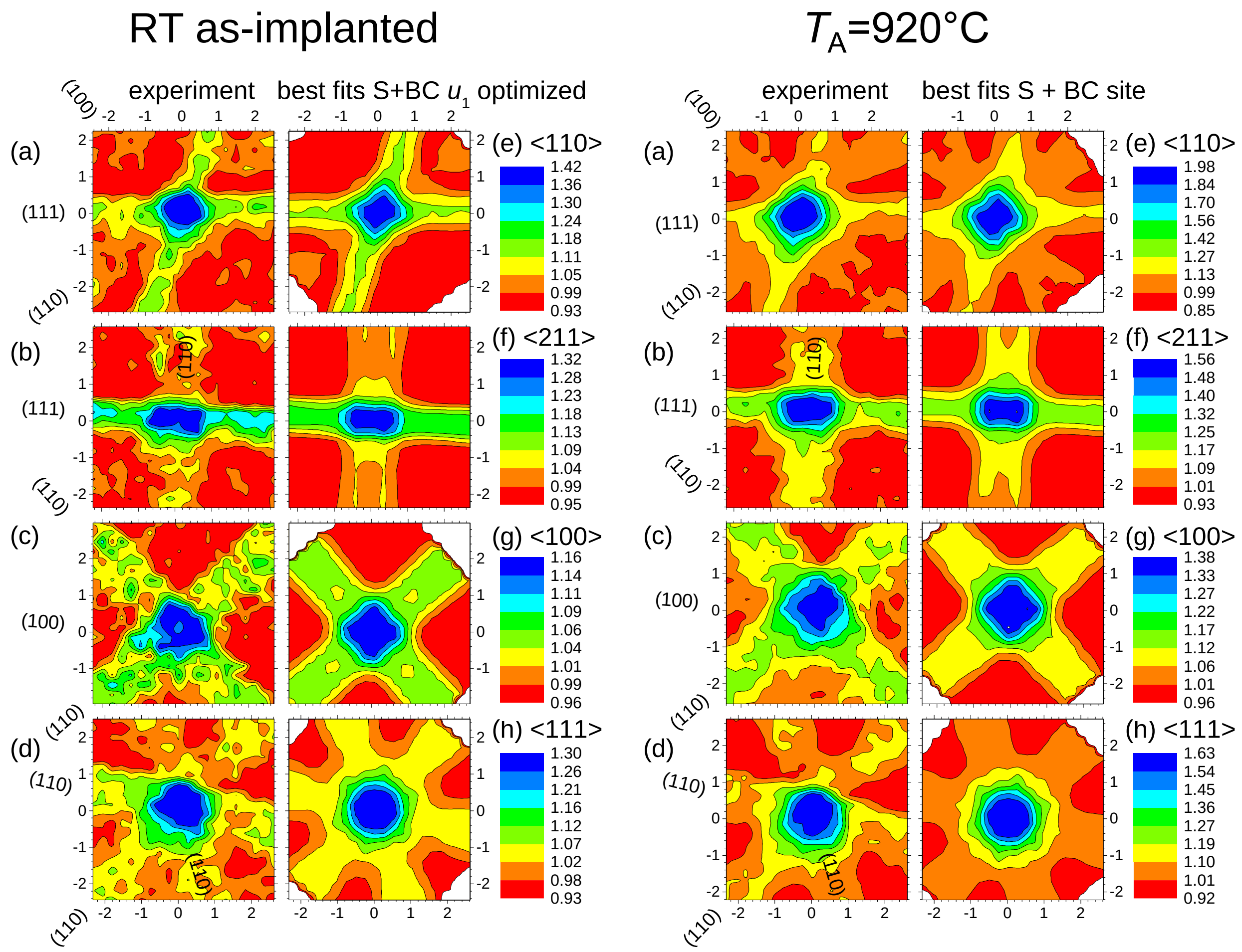
^{121}SnV - the tip of the iceberg



Direct structural identification and quantification of the split-vacancy configuration for implanted Sn in diamond

under review in Phys. Rev. Lett.

^{121}Sn*V*



- Strong channeling effects along all axial and planar directions indicate that ^{121}Sn substitutional sites must be involved.
- 920ºC annealing ~doubles the maximum yield (β^- anisotropy) of all patterns. A minority fraction is found on BC sites.
- <u>RT as-implanted:</u> best fits obtained for
  63% S with u_1=0.18 Å
  41% BC with u_1=0.11 Å
- <u>T_A=920°C:</u> best fits obtained for
  79% ideal S with u_1=0.034 Å
  32% ideal BC with u_1=0.034 Å

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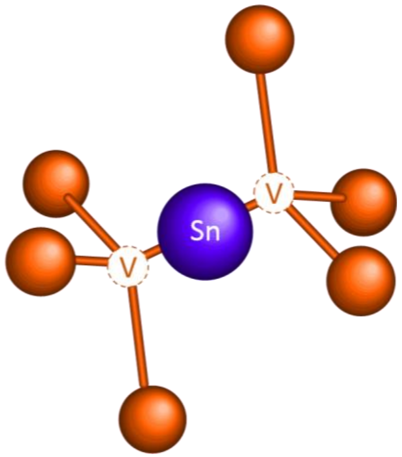
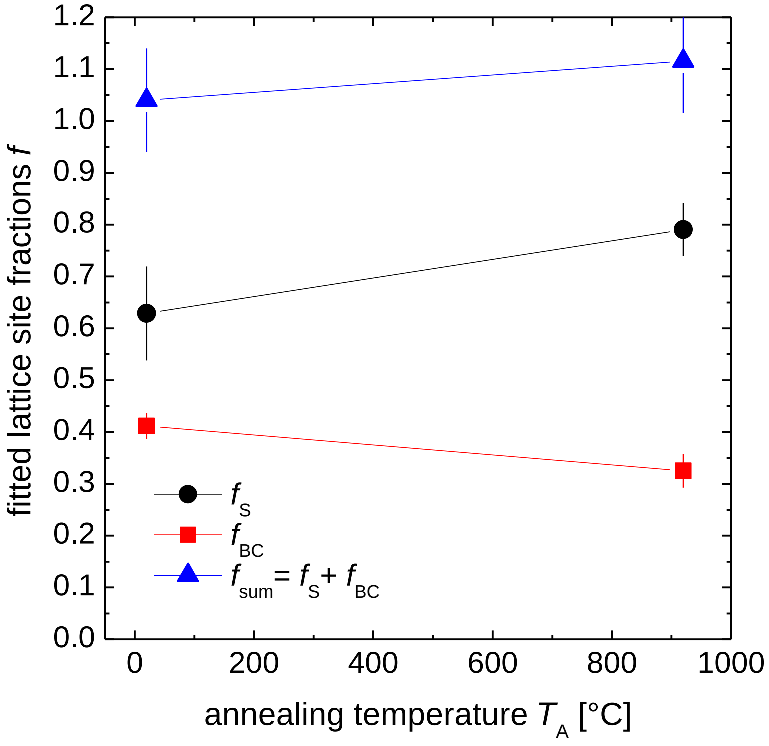
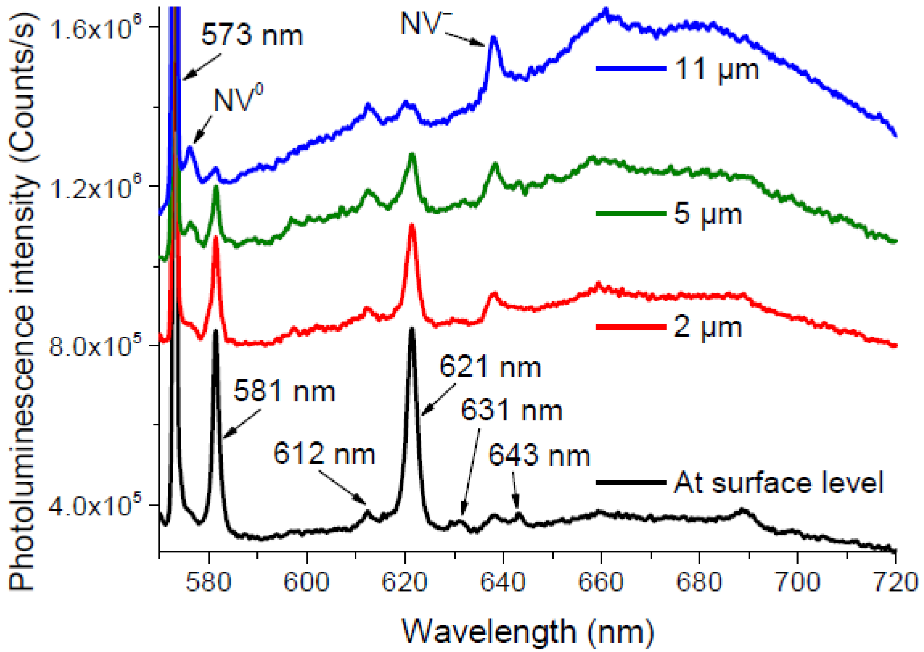
^{121}Sn*V*





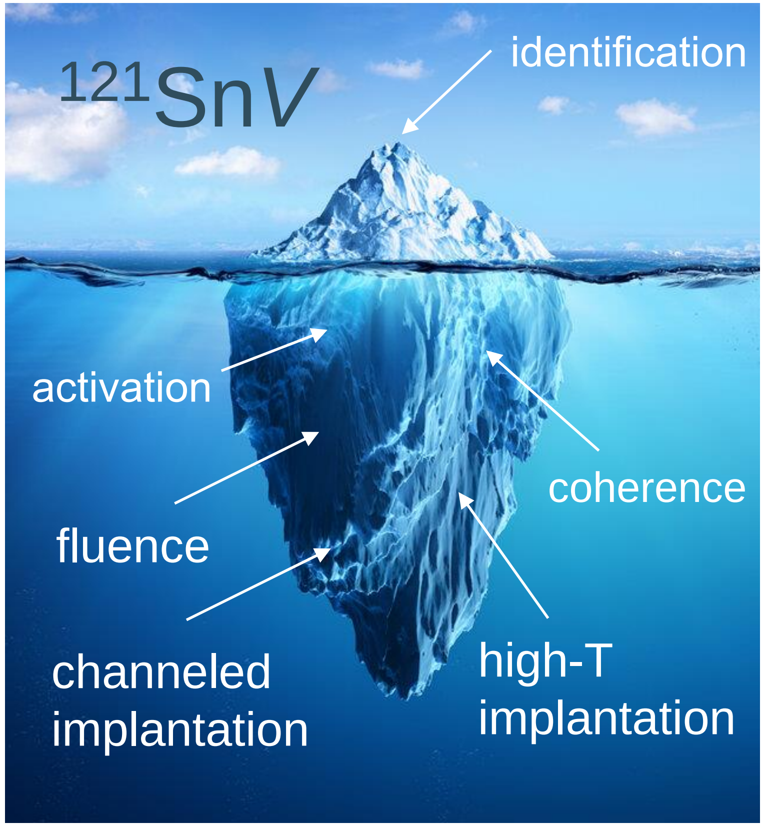


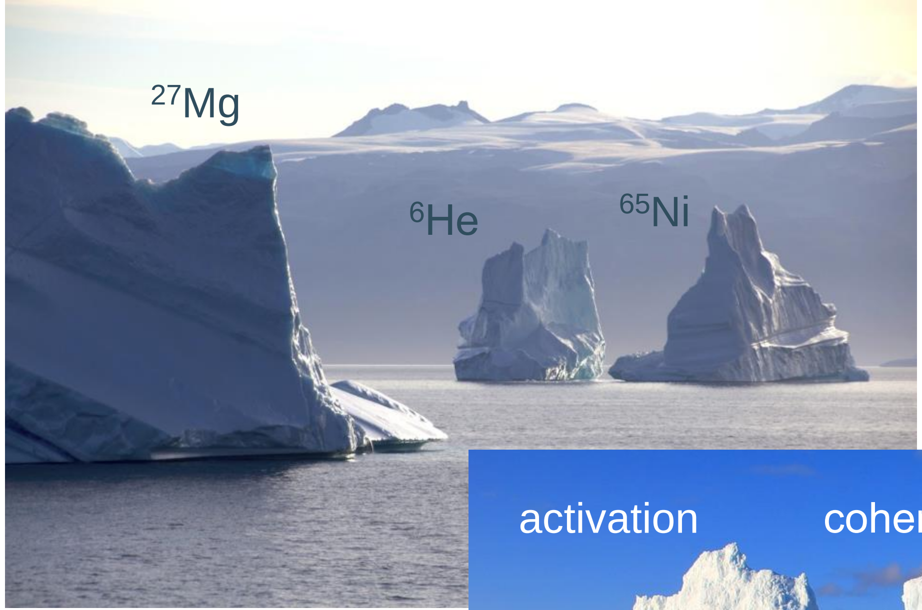
- Surprisingly high fraction of ^{121}Sn found on BC sites (= "split-vacancy" configuration) already in the as-implanted state.
- Besides reducing the rms displacements from S and BC sites, annealing at 920°C also converts some of the ^{121}Sn from BC sites to S sites.

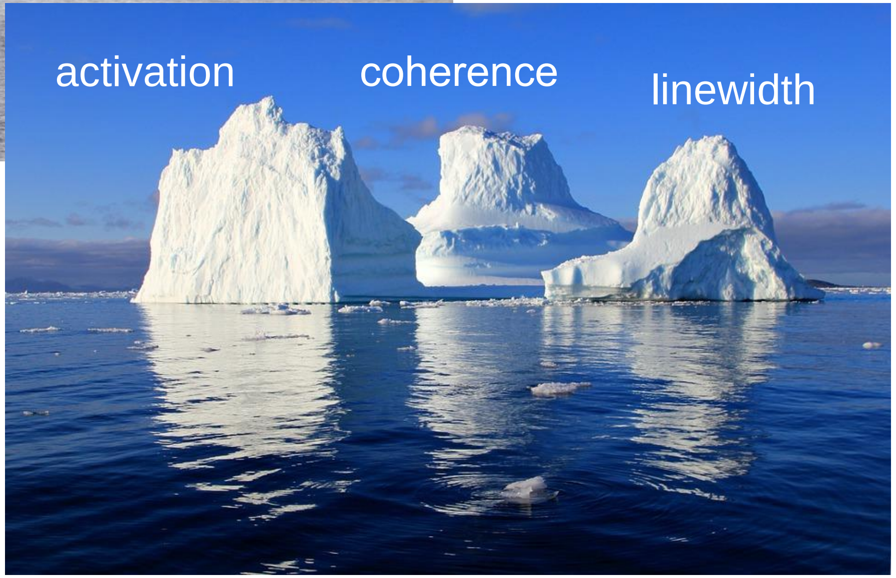
- RT as-implanted state dominated by broad lines around 586 nm and 614 nm (damage-related)
- 920ºC annealed: characteristic sharp PL line (FWHM 2.3 nm) from SnV^- at 621 nm [1,2,7] near the surface
- Still indirect assignment
  - **radiotracer PL will make it unambiguous**

[1] S.D. Tchernij *et al.*, ACS Photonics 4 (2017) 2580
[2] T. Iwasaki *et al.*, Phys. Rev. Lett. 119 (2017) 253601
[7] R. John *et al.*, New J. Phys. 19 (2017) 053008

^{121}Sn*V* - the tip of the iceberg (field)

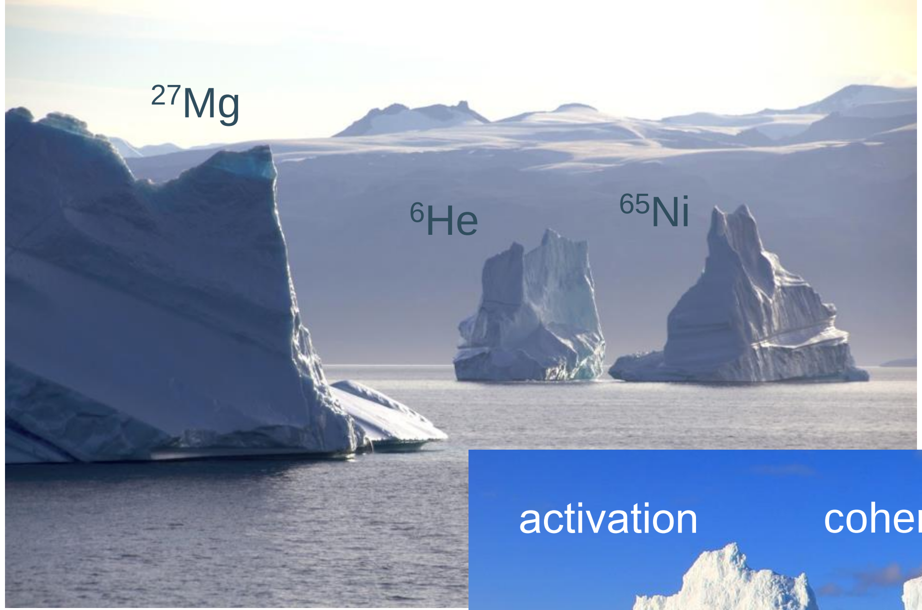


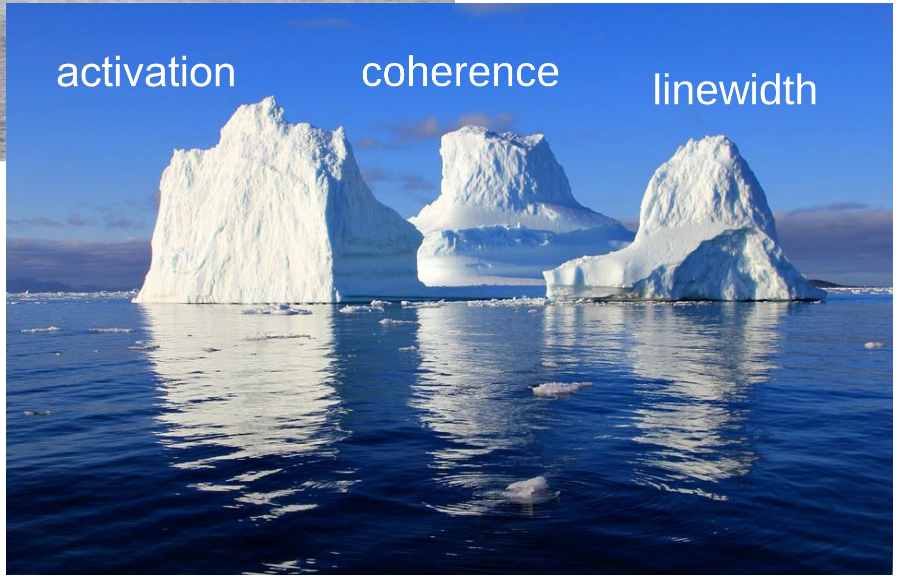




our proposal (INTC-P-562)

- study the lattice location of ion implanted impurities = structure of color centers in diamond using EC
- and correlate this information with the optical properties of the centers as determined by radiotracer PL
- only experimental approach capable of directly providing that information
- investigate the fabrication optimization (influence of implantation temperature and of implantation under channeling conditions)
- focus on Sn*V*
- other color centers of interest (promising/proposed) will be addressed depending on beam availability and progress in the field: Si, Ge, Pb, Mg, Ca, Sr, Ni, He, Ne, Ar, Kr, Xe





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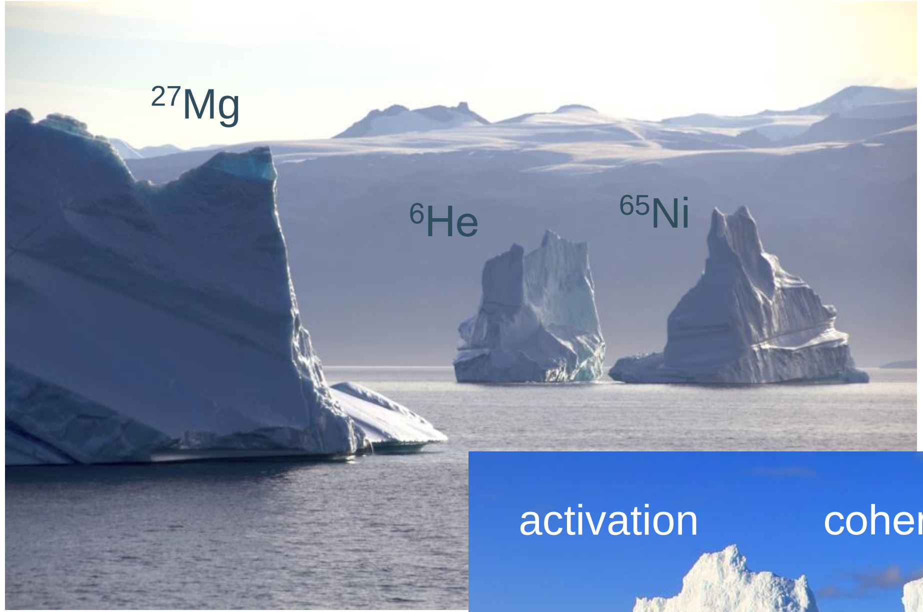
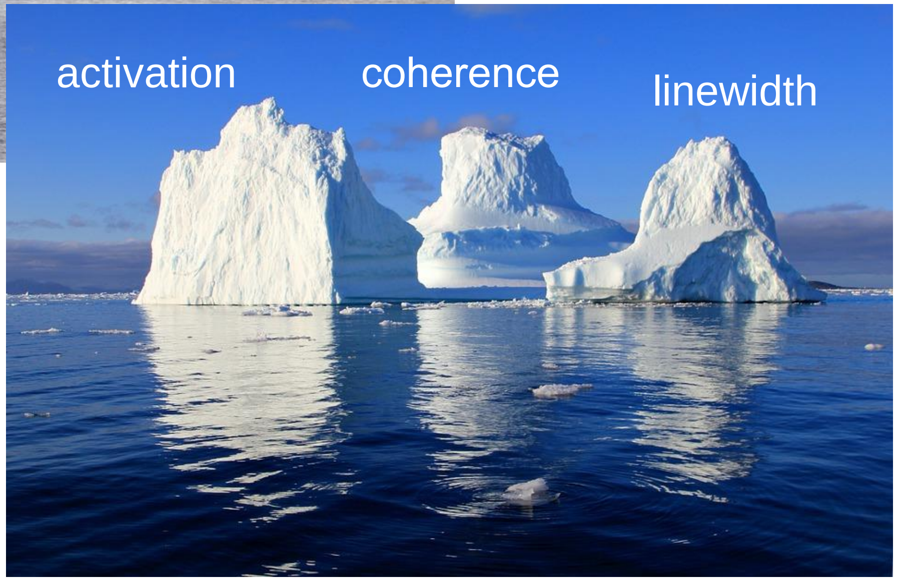
our proposal (INTC-P-562)

perfect **match** between the needs of the field and the (unique) characteristics/strengths of our approach

- doping by ion implantation ✓
- low fluence ✓
- direct and unambiguous defect structure ✓
- direct and unambiguous correlation between defect structure and optical signature ✓





strategic value

- critical research field in Europe/world
- extensive and high-impact scientific output expected
  - optimal use of flexible “parallel beam”
  - different groups in the collaboration with specific interest/experience with different defects
    - with extensive in-house facilities for complementary experiments/development
- high potential to attract new high-profile users (SSP)

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isotope	half-life	yield (atoms/μC)	target - ion source	Shifts (8h)
^{121}Sn	27.06 h	1×10^8	UC_x-W - RILIS Sn	8
^{27}Mg	9.5 min	1×10^7	Ti-W - RILIS Mg	2.5
^{28}Mg	21 h	6×10^6	Ti-W or UC_x-W - RILIS Mg	0.25
$^{45}K\rightarrow^{45}Ca$	17.3 min→164 d	1×10^7	UC_x-W	0.5
$^{89}Rb\rightarrow^{89}Sr$	15.5 min→50.5 d	7×10^9	UC_x-W	0.25
^{65}Ni	2.52 h	7×10^7	UC_x-W - RILIS Ni	0.5
^{6}He	807ms	7×10^7	UC_x or BeO plasma	3.0
^{23}Ne	37.2 s	1.6×10^6	UC_x plasma	1.0
^{41}Ar	109 min	1.6×10^6	UC_x or TiO_2 plasma	0.5
^{87}Kr	76.3 min	2×10^8	UC_x or PbBi plasma	0.25
^{133}Xe	5.2 d	3×10^7	PbBi, ThC or UC_x plasma	0.25
^{135}Xe	9.1 h	1.5×10^8	ThC or UC_x plasma	0.25
$^{31}Al\rightarrow^{31}Si$	644 ms→157 min	2.5×10^5	UC_x-W - RILIS Al	2
$^{75}Ga\rightarrow^{75}Ge$	126 s→82.8 min	3×10^7	UC_x-W - RILIS Ga	0.5
^{209}Pb	3.25 h	no yield in data base	UC_x-Nb - RILIS Pb or LIST Pb	0.5

green - EC only
blue - also suitable for radiotracer PL
red - precursors that decay to desired probe

most isotopes can be produced from UC-W or UC-plasma target-ion source

number of shifts per isotope: tentative
(flexibility, in coordination with other users)

we do not expect to cover all listed isotopes within the next 2 years

fast-moving field
but flexibility allows us to adapt