Designing new ultra-radiopure, high-strength electroformed Cu-based alloys, for rare event searches

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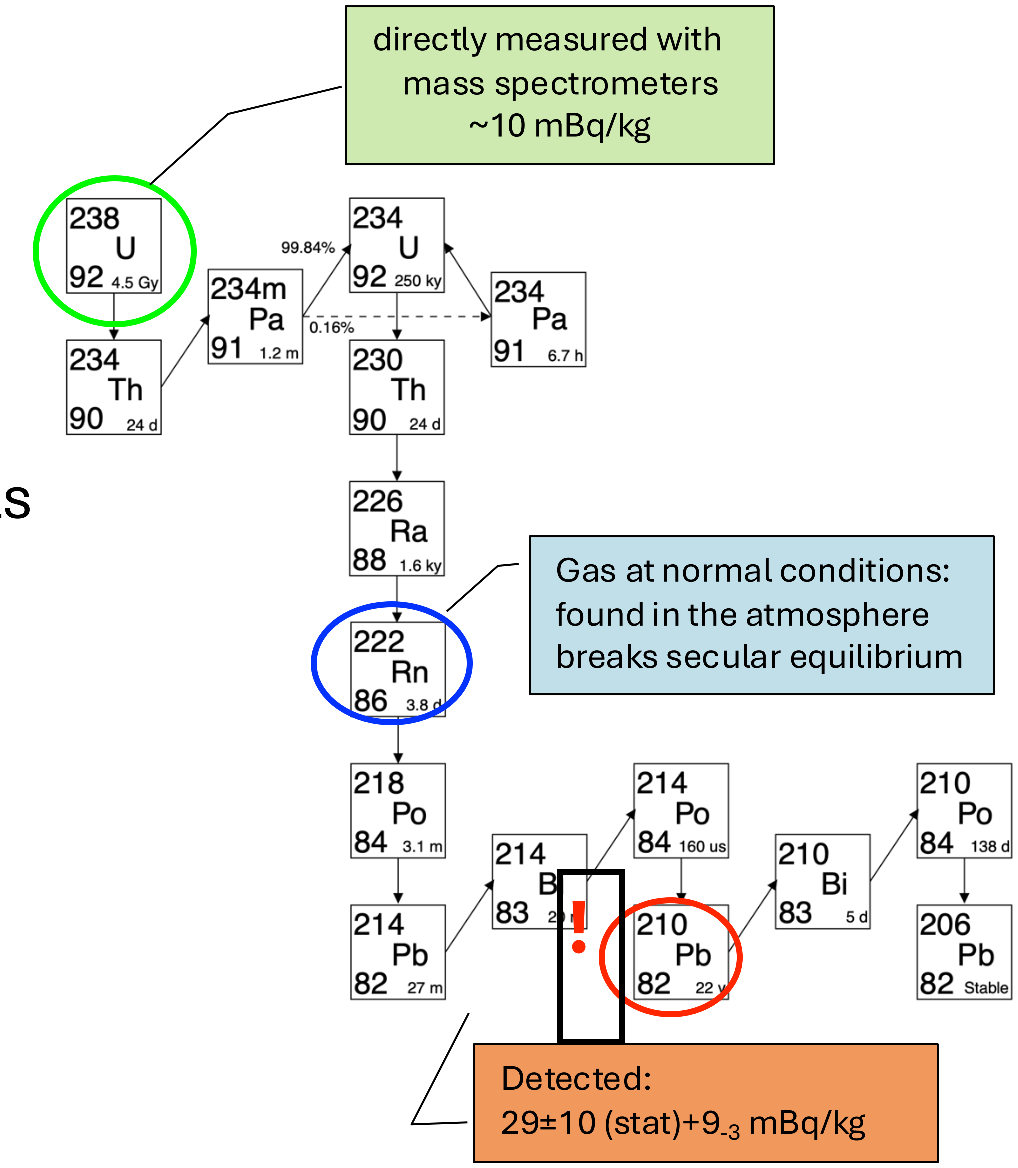
Radiopure Cu for rare event searches

- Cu: common material for rare event searches experiments
  - ✓ Electrically conductive
  - ✓ Strong enough to build low-pressure gas vessels
  - ✓ No long-lived isotopes (^{67}Cu $t_{1/2}$=62h)
  - ✓ Low cost/commercially available at high purity

- Backgrounds
  - ✓ Cosmogenic: $^{63}Cu(n,\alpha)^{60}Co$ from fast neutrons
  - ✓ Contaminants: ^{238}U/^{232}Th decay chains



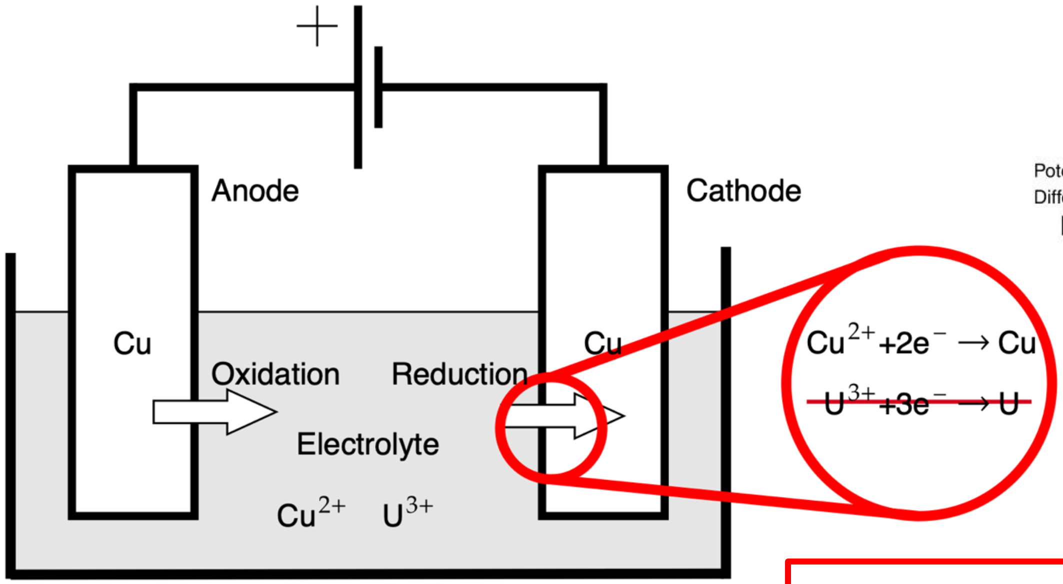
Electroformed Cu (EFCu) for rare event searches

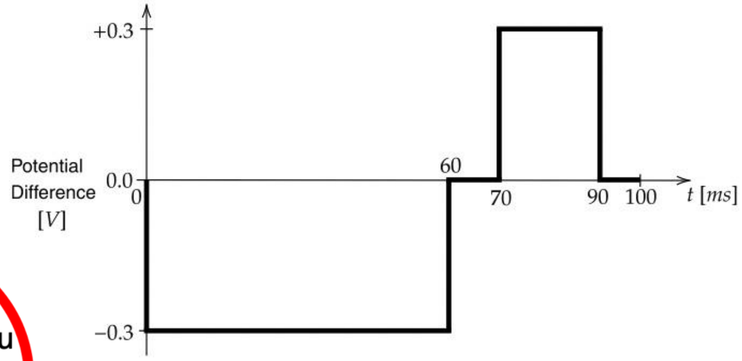
Reduction potential for copper and possible radiocontaminants.

Reductants		Oxidants	E^0 (V)
$Cu^{2+} + 2e^-$	⇋	Cu	+0.34
$Pb^{2+} + 2e^-$	⇋	Pb	−0.13
$U^{3+} + 3e^-$	⇋	U	−1.80
$Th^{4+} + 4e^-$	⇋	Th	−1.90
$K^+ + e^-$	⇋	K	−2.93

Giovanni Rogers
Poster/ 136

rare event searches:
e.g. LEGEND, NEWS-G, ANAIS, Majorana, nEXO DarkSPHERE





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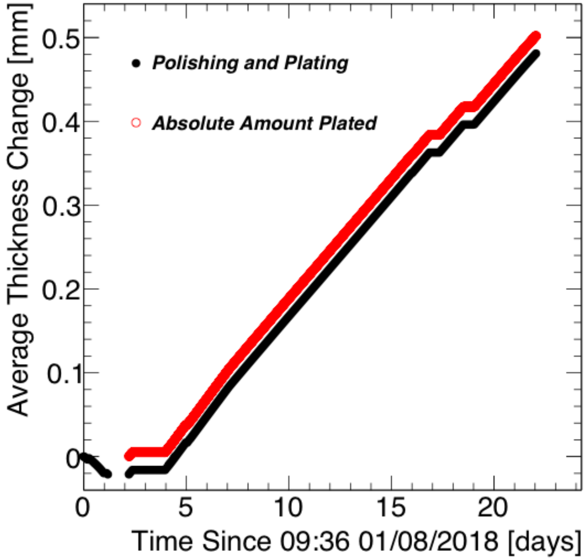
Cu 'High reduction potential'

→ Preferentially deposited → Additive-free, electroforming

Ultra-pure Cu electroforming

Majorana Demonstrator



~1 mm/month

#	Material	Method	K (10^{-9} g/g)	^{232}Th (10^{-12} g/g)	^{238}U (10^{-12} g/g)
	Metals				
1	Cu Electroformed Stock Sample	ICPMS		<0.17	
2	Cu Electroformed Stock Sample	ICPMS		0.011±0.005	0.017±0.003
3	Cu Electroformed Stock Sample	GDMS	<2.2	<50	<70
4	Cu Electroformed Stock Sample	ICPMS		<0.029	<0.008
5	Cu Electroformed Stock Sample	ICPMS		<0.029	<0.009
6	Cu Electroformed Stock Sample	ICPMS		<0.029	<0.008
7	Cu Electroformed Stock Sample	ICPMS		<0.030	<0.009
8	Cu Electroformed, machined part, guide clip	ICPMS		0.330 ± 0.022	0.123 ± 0.005
9	Cu Electroformed, machined part, guide clip	ICPMS		0.112 ± 0.009	0.078 ± 0.002
10	Cu Electroformed, machined part, guide clip	ICPMS		0.170 ± 0.008	0.087 ± 0.002
11	Cu Electroformed, machined part, spring clip	ICPMS		0.215 ± 0.009	0.130 ± 0.010
12	Cu Electroformed, machined part, hex bolt	ICPMS		0.118 ± 0.011	0.035 ± 0.004
13	Cu Electroformed, machined part, hex bolt	ICPMS		0.119 ± 0.014	0.041 ± 0.003
14	Cu Electroformed, machined part, hex bolt	ICPMS		0.148 ± 0.021	0.051 ± 0.002
15	Cu, C10100 cake stock, (source for Rows 16,17)	ICPMS		0.46 ± 0.06	0.21 ± 0.06
16	Cu, C10100 2.5” plate stock, exterior sample	ICPMS		0.27±0.05	0.10±0.02
17	Cu, C10100 2.5” plate stock, interior sample	ICPMS		0.27±0.05	0.12±0.02
18	Cu, C10100 1” plate stock, saw cut (same stock Row 19)	ICPMS		10.2 ± 1.0	6.62 ± 0.58
19	Cu, C10100 1” plate stock, machined surfaces	ICPMS		1.88 ± 0.45	3.11 ± 0.39
20	Cu, C10100 1” x 2” bar stock, machined surfaces	ICPMS		2.12 ± 0.39	2.25 ± 0.15
21	Cu, C10100 1” plate stock	ICPMS		<0.029	0.013 ± 0.002
22	Cu, C10100 2.5” plate stock	ICPMS		<0.030	0.017 ± 0.003
23	Cu, C10100 2.5” plate stock	ICPMS		0.049 ± 0.010	0.061 ± 0.006
24	Cu, C10100 0.5” plate stock	ICPMS		<0.030	0.009 ± 0.001

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- ✓ 500 µm electroplated layer to NEWS-G detector inner surface
- ✓ Demonstrated potential to electroform full detector on feasible time scale

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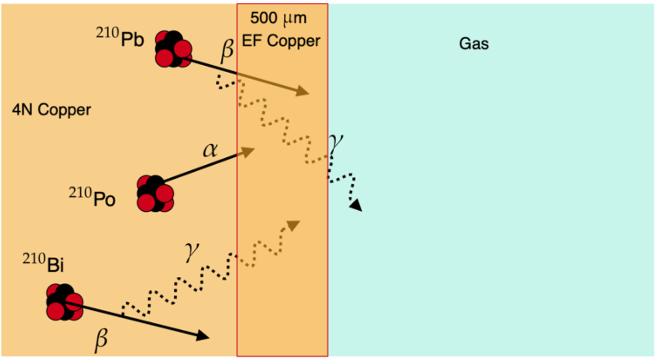
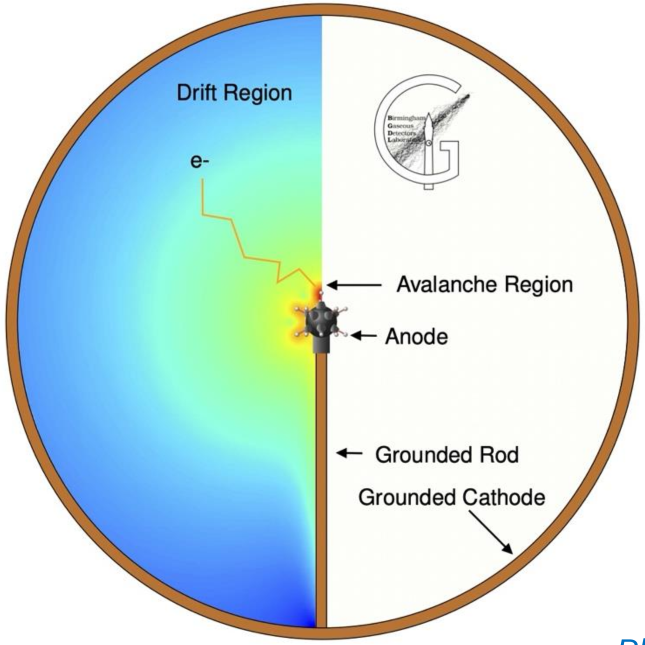


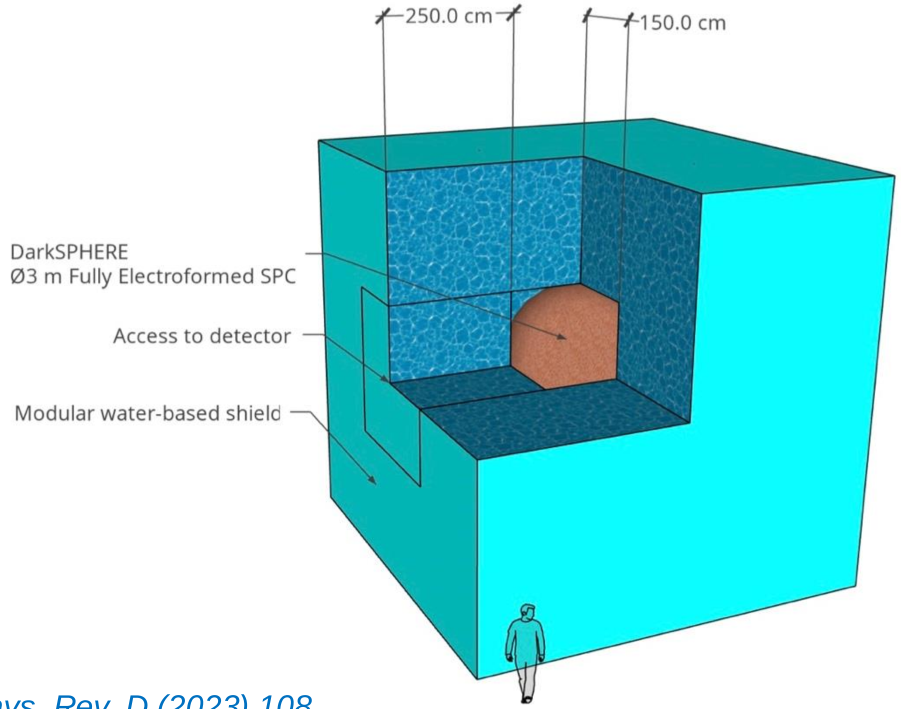
Motivation of ultra-pure, high-strength Cu-based alloys

- ✓ Retain EFCu capabilities for rare event searches
- ✓ Option for stronger material compared to Cu
- ✓ Scale up the current geometries for gas vessels (i.e. maximising the physics potential in DM experiments)

<u>fundamental science applications</u>:
e.g. nEXO, NEXT, DarkSPHERE

<u>other applications</u> (<u>not radiopure</u>):
- Electronic circuits
- Storage technology





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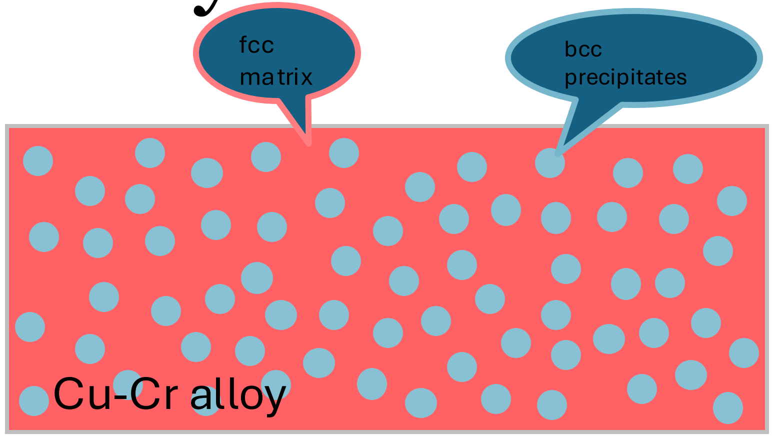
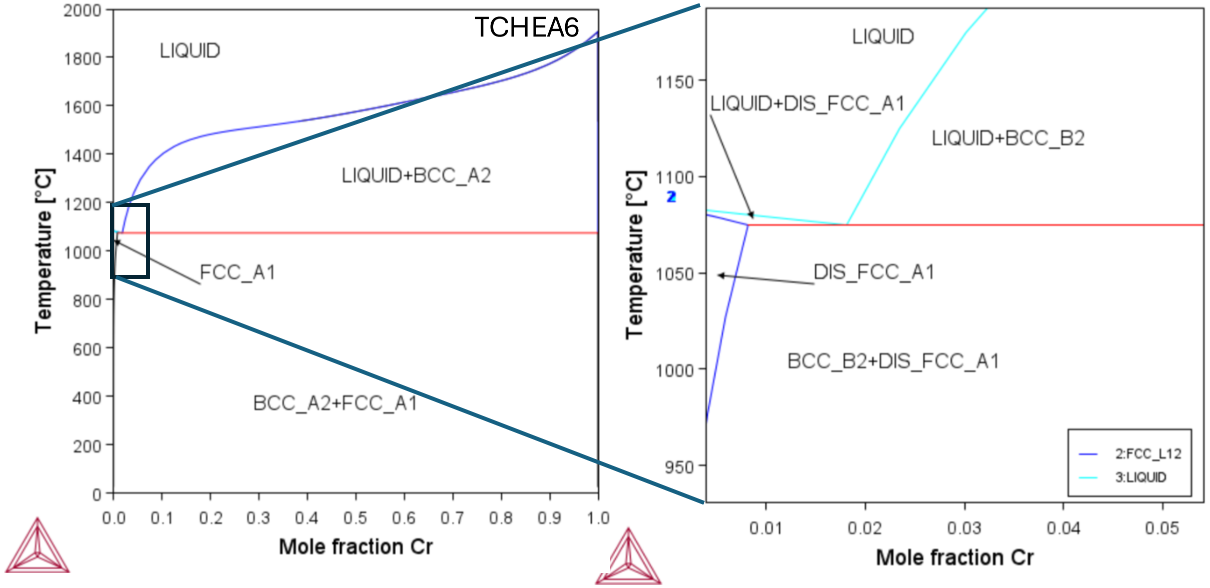
Strengthening mechanisms in CuCr alloys



- ✓ retain Cu electrical conductivity
- ✓ stronger than Cu
- ✓ radiopure

DICTRA or TC-PRISMA : TCHEA6-MOBHEA3 (TC High Entropy Alloys database)



- Solution heat treatment (homogenisation)

1025°C - 1050°C

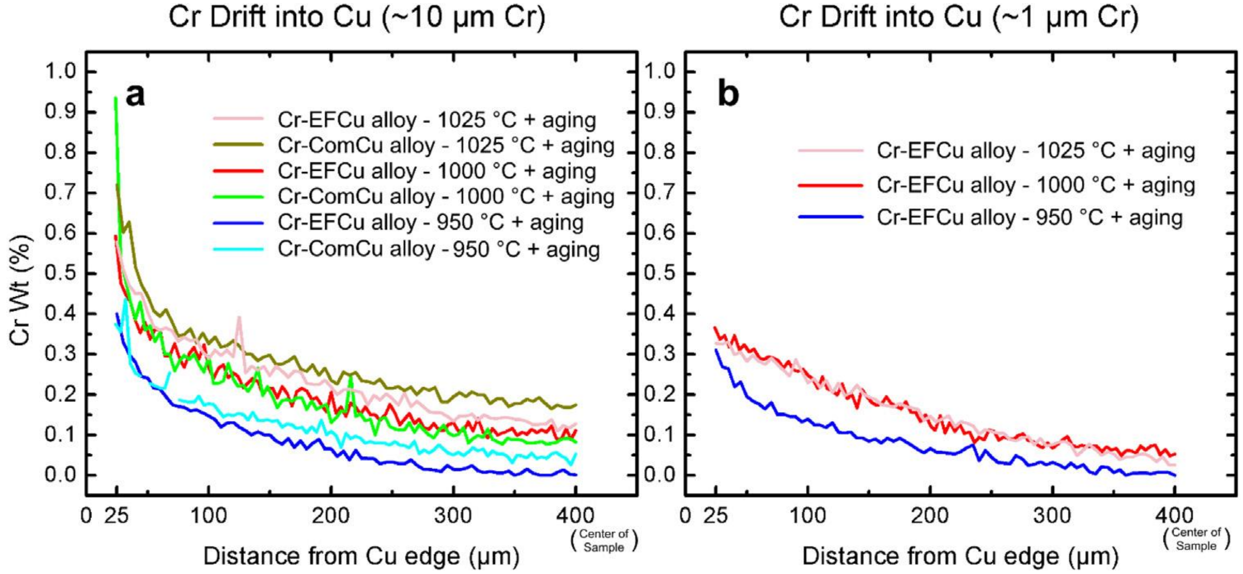
- Precipitation strengthening (aging)

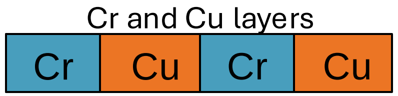
400°C - 500°C

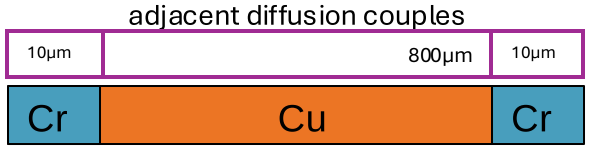
Alloying EFCu with Cr additions

1. Cr and Cu layers from separate solutions
2. Solution heat treatment at **1000ºC** (homogenisation)
3. Aging at **400ºC – 12 hours** (precipitation strengthening)

Sample	[Th] pgTh/gSample	±sd	[U] pgU/gSample	±sd
EFCu	0.011	0.005	0.017	0.003
Cr	8.72	0.32	2.37	0.61
Cu-Cr(0.585wt%) projection	0.062	0.007	0.031	0.007

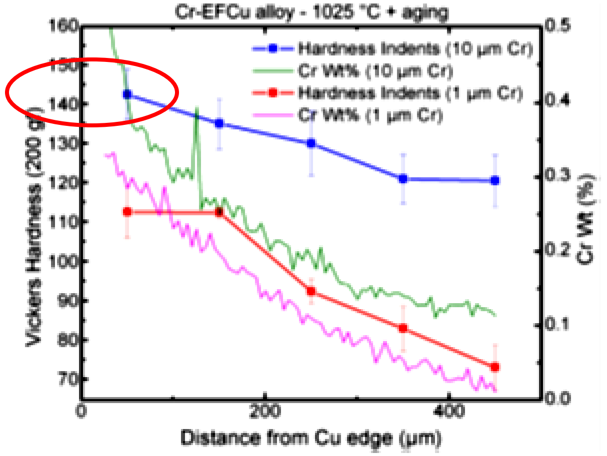






~70% harder

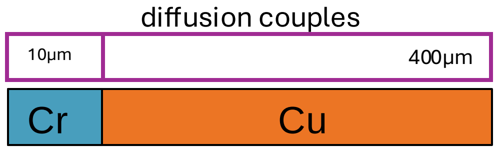
EFCu	72 HV
Cu-0.585Cr	121 HV



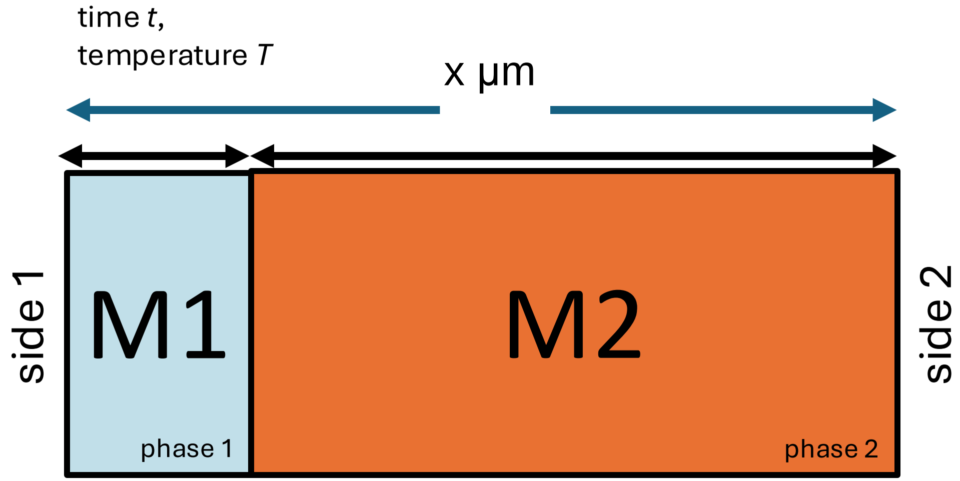
Suriano et. al. AIP Conf. Proc. 1921, 1003 (2018) 080001

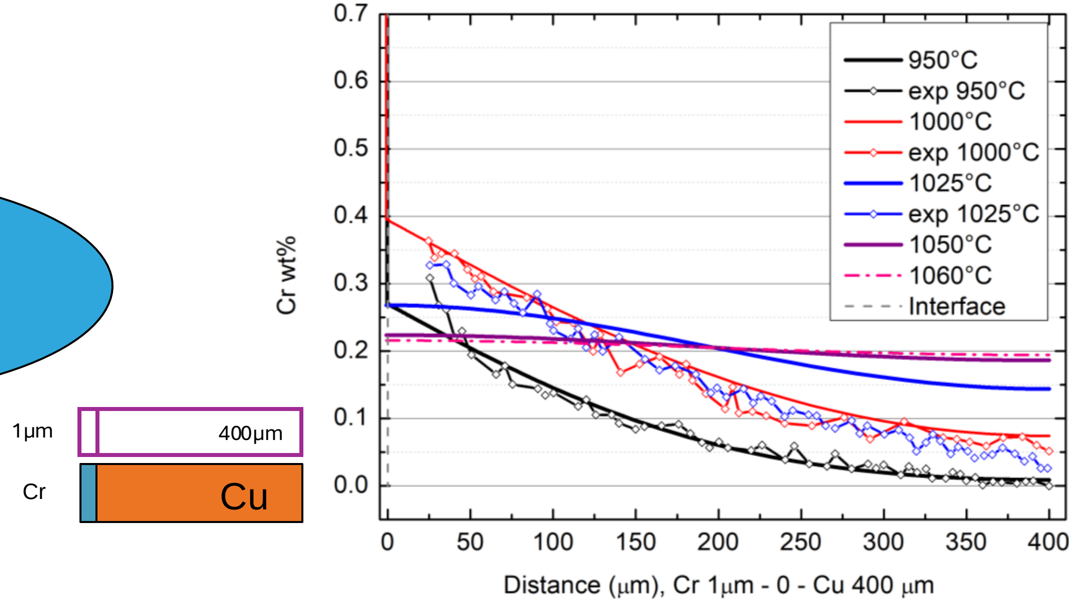
A. Vitale et. al. Nuclear Inst. and Methods in Physics Research, A 1003 (2021) 165291

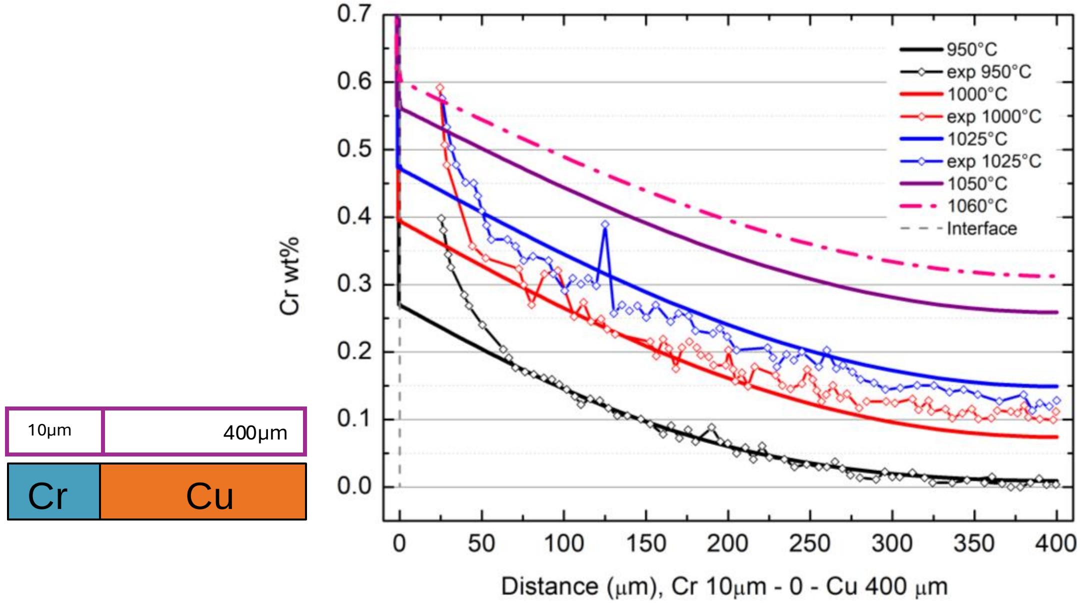
Modelling solution heat treatment



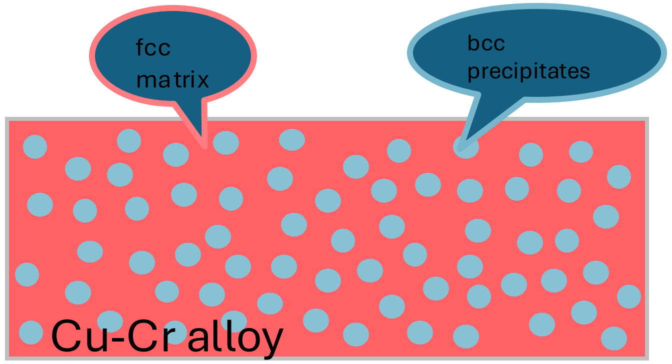
Predict *t* and *T* for solution heat treatment



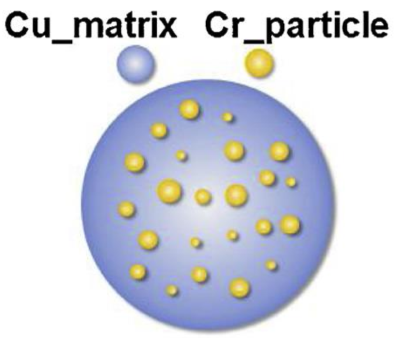




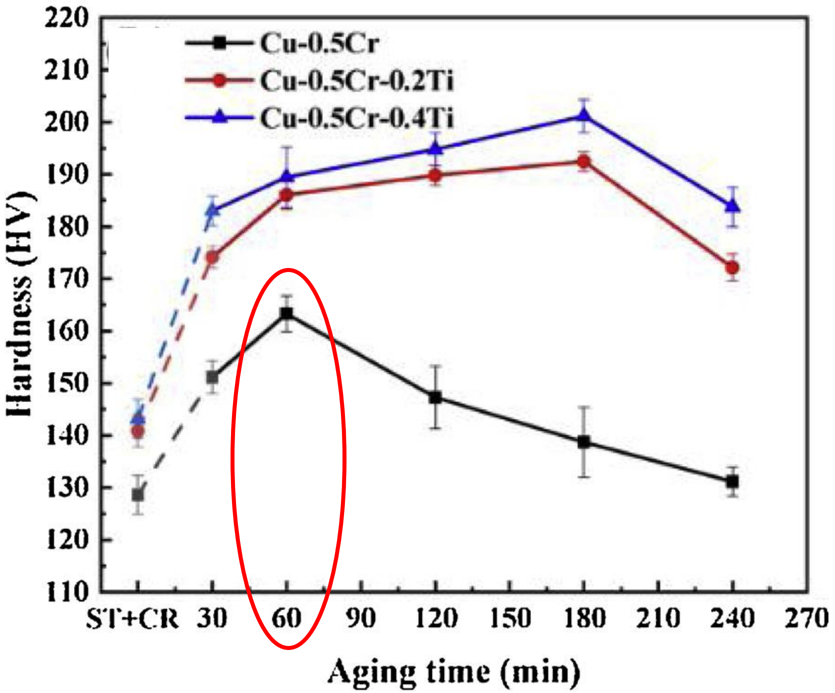
Modelling precipitation strengthening



Predict *t* and *T* for aging



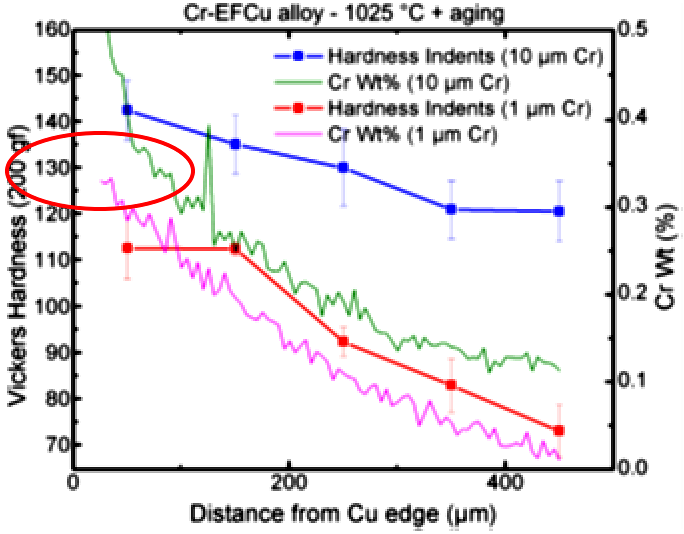
450°C – 60 min



Cu-0.5Cr	150 HV
Cu-0.5Cr0.2Ti	230 HV
Cu-0.5Cr0.4Ti	280 HV

Huang et. Al 2021

500°C – 12 hours



Cu-0.4Cr	140 HV

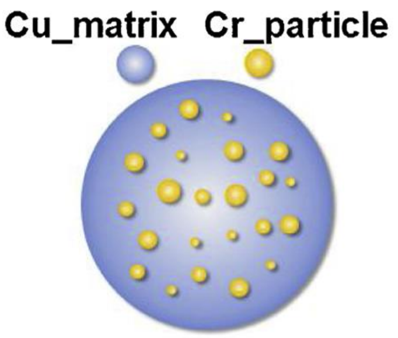
Vitale et al. 2021

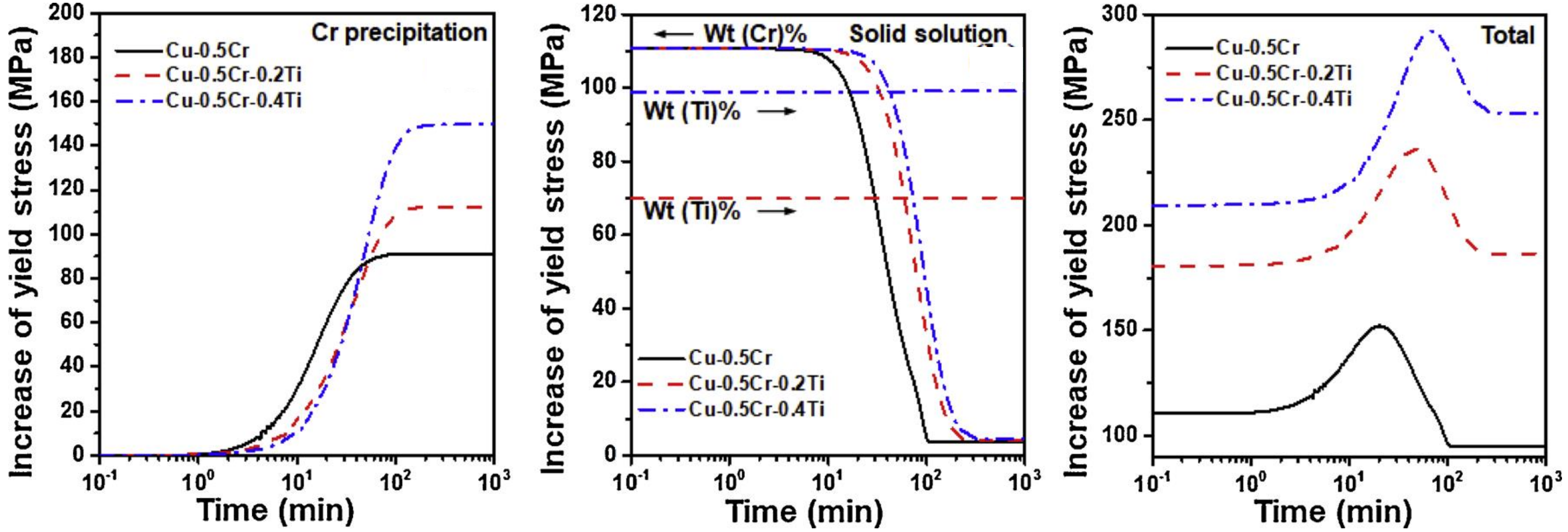
EFCu	72 HV
Cu-0.585Cr	121 HV

Suriano et. al. 2018

Optimising aging parameters

Prior aging @450°C:
Solution heat treatment (as-cast) – cold work (90% total deformation)
Interfacial energy: 0.68 - 0.72 J/m^2





Cu-0.5Cr aging at 450ºC for 60min → peak strength

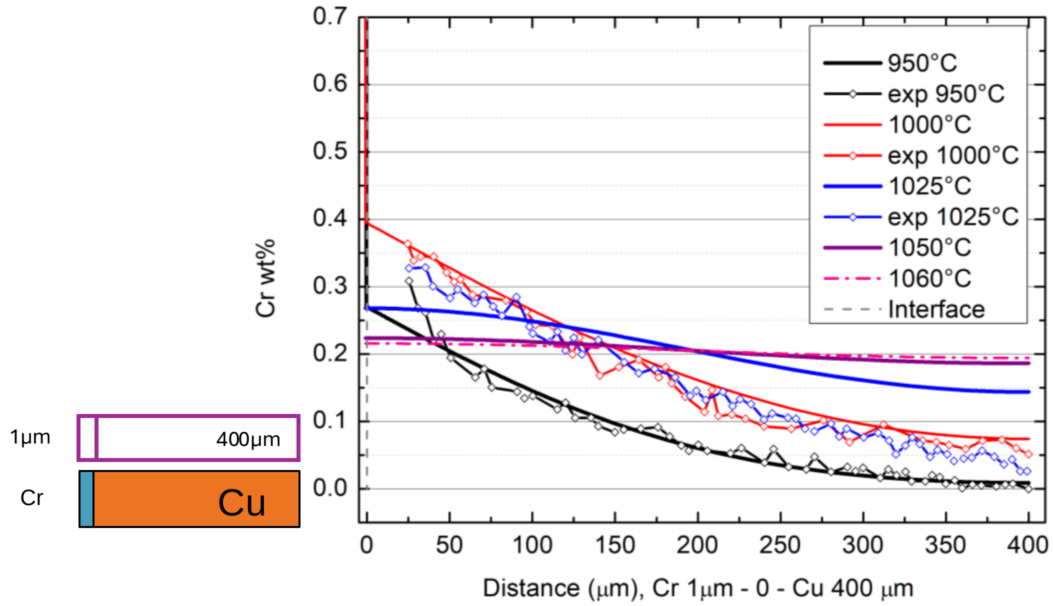
Outputs (temporal evolution) for Yield strength:

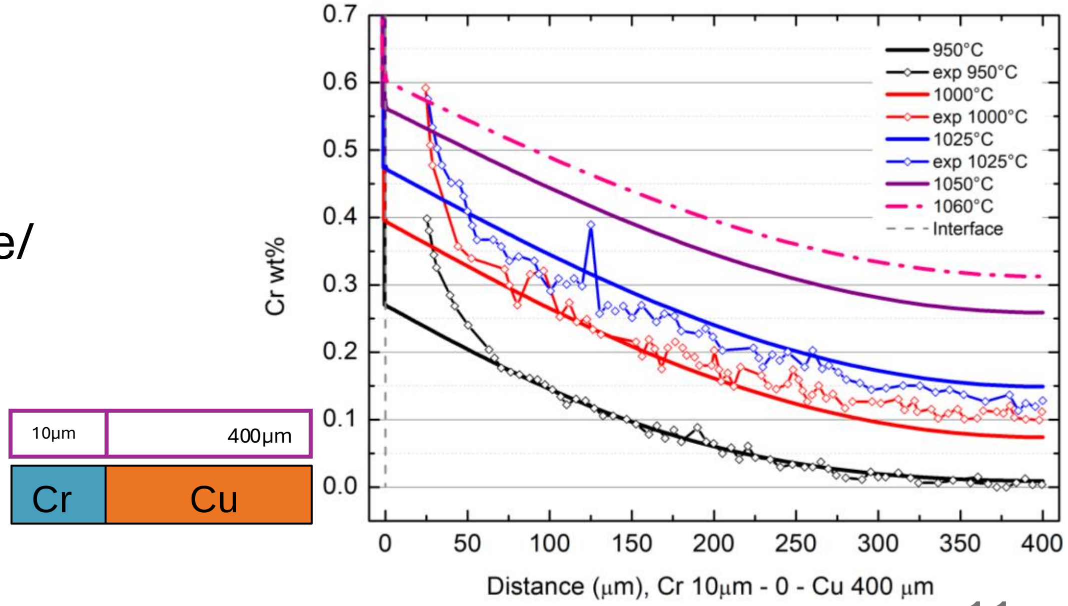
- ✓ radius precipitate (nm)
- ✓ Volume fraction % precipitate
- ✓ Cr concentration in matrix

Z. Huang et. al, Mater Today Comms (2021), 102378

Conclusions

- ✓ Radiopure materials are extremely important for rare event searches experiments
- ✓ Cu is the material of choice, but enhanced mechanical properties are required
- ✓ Cu-based alloys are suggested as promising alternative
- ✓ Based on early experimental trials, synthesis of Cu-based alloys is possible during electrodeposition
- ✓ Solution heat treatment simulations validated – aging time/ duration needs to be explored further with experiments
- ✓ Modelling tools are available to study and optimise the process, with confirmed findings as a starting point





Thank you for your attention!

focusing on
ultra-radiopure, high strength Cu-based alloys