Overview of Sub-Kelvin Technologies

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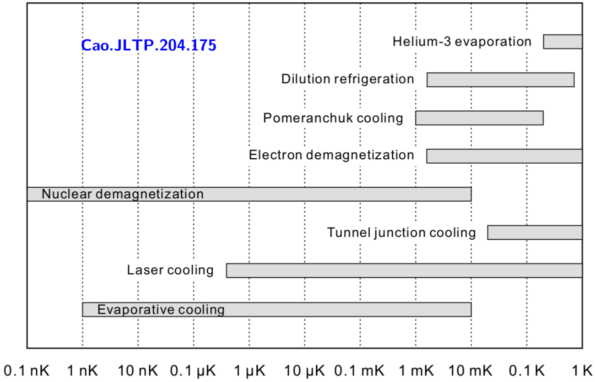
Outline

Introduction



Focus

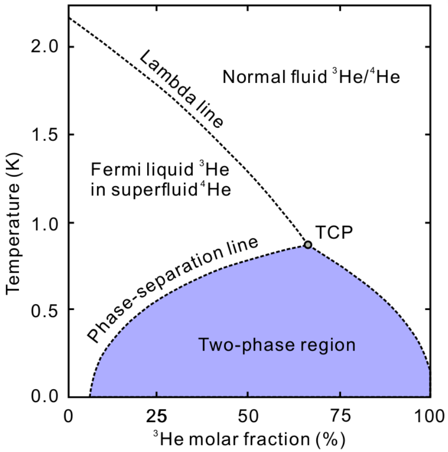
- dilution refrigeration
- ADR (continuous)
- comparison

My background

- current work: ^{3}He-^{4}He dilution refrigeration in micro-gravity
- 45 years ago: ADR

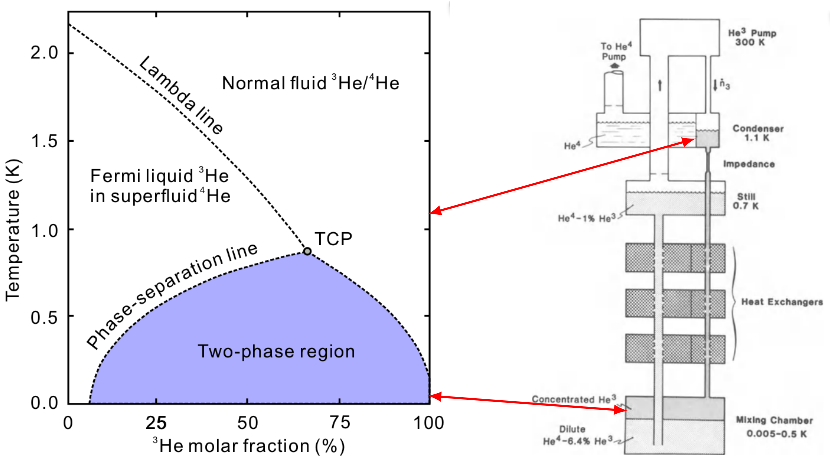
Outline

Helium-3 Dilution Refrigeration



Pobell.Chapter.Springer.7.2007; **Cao.JLTP.204.175**; **Walker.Book.2.Springer.1983**

Helium-3 Dilution Refrigeration



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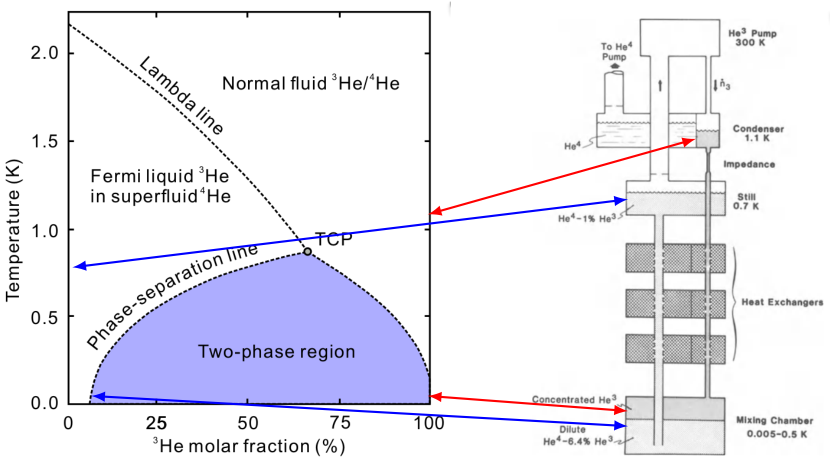
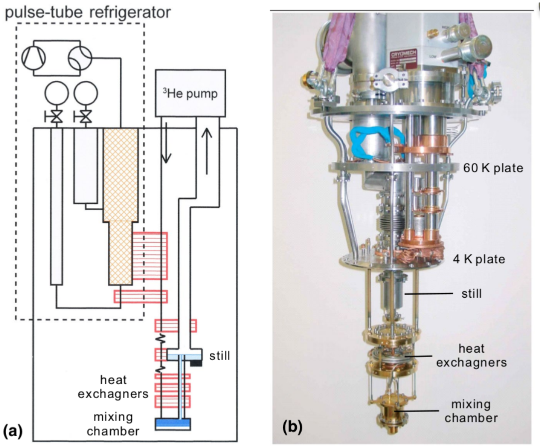


$$\dot{Q}_{\mathrm{mc-thermo}} \approx \alpha \dot{n}_3 \left(T_{\mathrm{dil}}^2 - T_{\mathrm{con}}^2 \right) \text{ with } \alpha \approx 82\,\mathrm{J\,mol^{-1}\,K^2}$$

in my opinion: 50 % of $\dot{Q}_{\mathrm{mc-thermo}}$ means good work

Pobell.Chapter.Springer.7.2007; **Cao.JLTP.204.175**; **Walker.Book.2.Springer.1983**

Dry Helium-3 Dilution Refrigeration



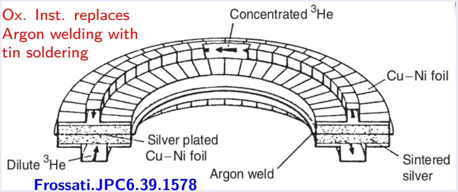
Cao.JLTP.204.175

more sample space

no liquid ^{4}He costs

Dilution Refrigerator Heat Exchange

1978: best heat exchanger layout



today

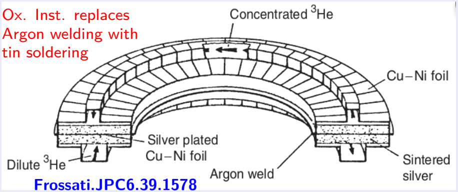
- 5 mK instead of 2 mK
- 10 times more ^{3}He flow rate

construction details

- electroplate Cu-Ni foil with Ag
- sinter Ag powder at $\approx 200\,°C$
- Ag messes up Argon welding

Dilution Refrigerator Heat Exchange

1978: best heat exchanger layout



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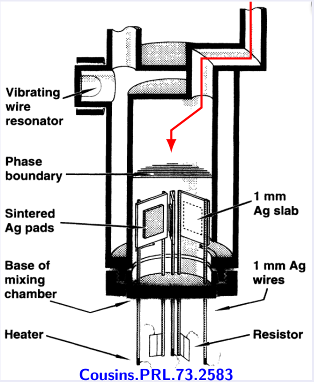
mixing chamber geometry



poor liquid thermal conductivity

- force ^{3}He over vertical slabs

Dilution Refrigerator Heat Exchange

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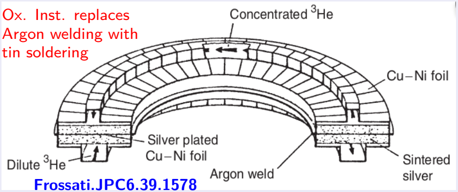

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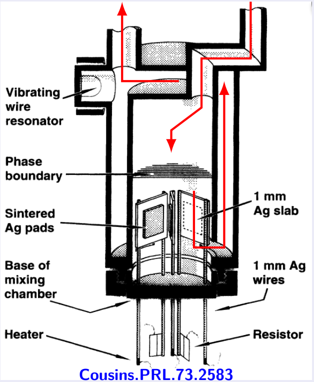

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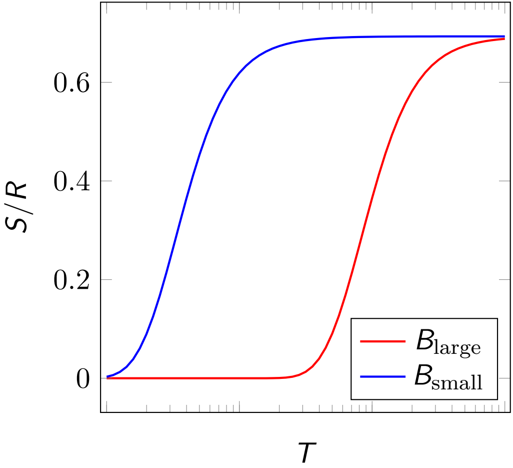
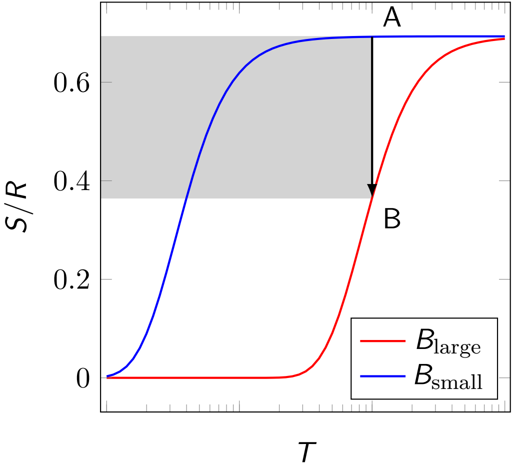
Outline

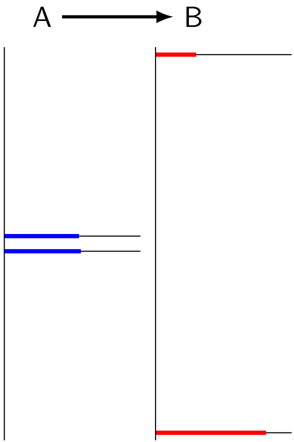
Adiabatic Demagnetization Refrigeration Principles



spin-1/2: textbook Carnot diagrams have S- and T-axes swapped

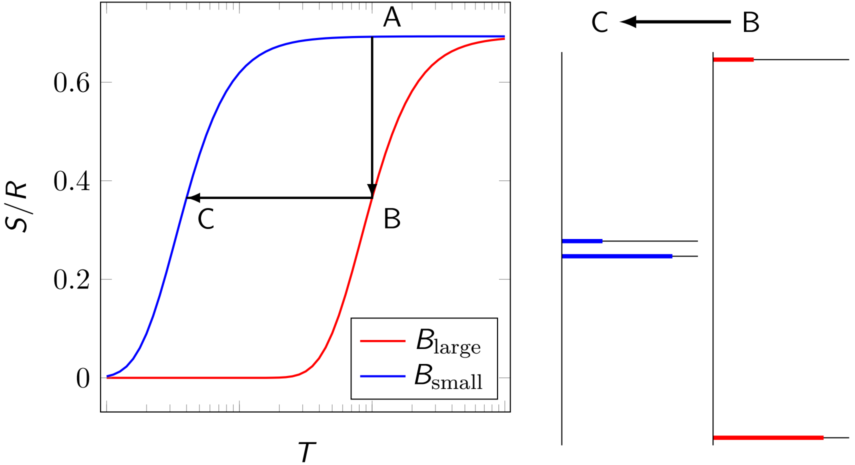
Adiabatic Demagnetization Refrigeration Principles





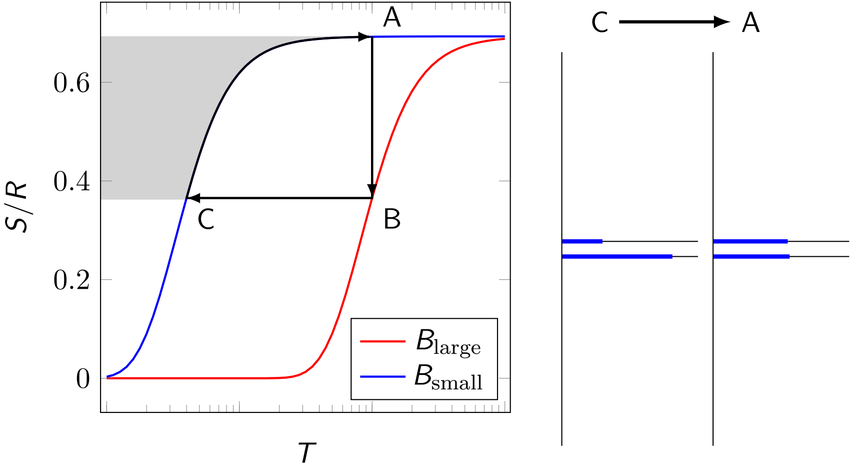
on earth: isothermal $B \Uparrow$ dumps heat (grey area) to temperature bath

Adiabatic Demagnetization Refrigeration Principles



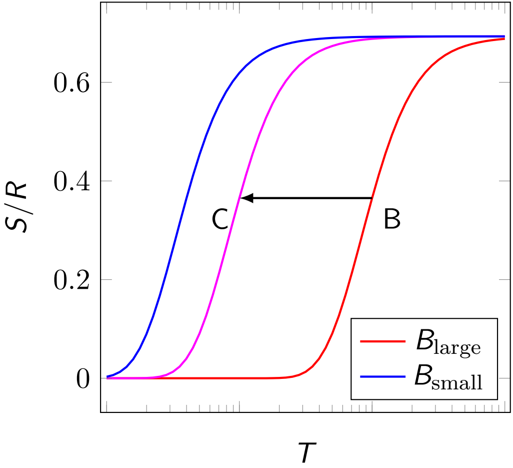
on earth: adiabatic $B \Downarrow$ implies spin system $T \Downarrow$

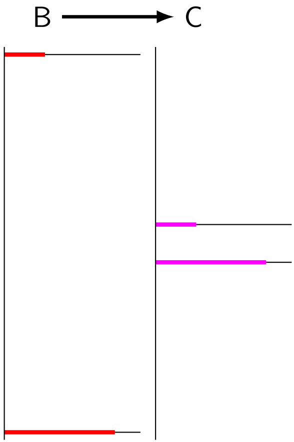
Adiabatic Demagnetization Refrigeration Principles



on earth: the system lifts heat (grey area) while it warms up

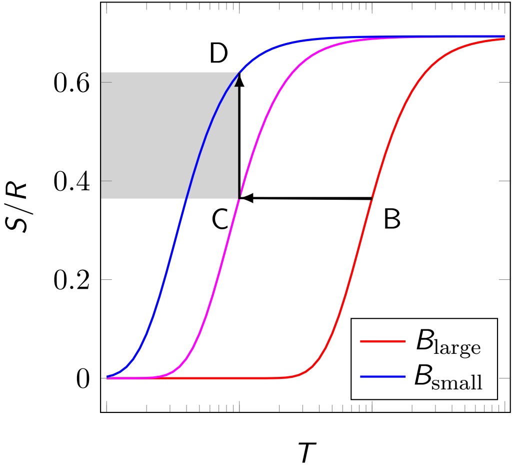
Adiabatic Demagnetization Refrigeration Principles

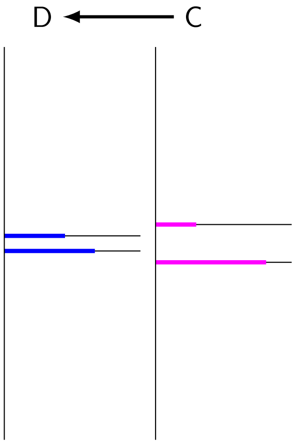




in space: adiabatic $B \Downarrow$ implies spin system $T \Downarrow$

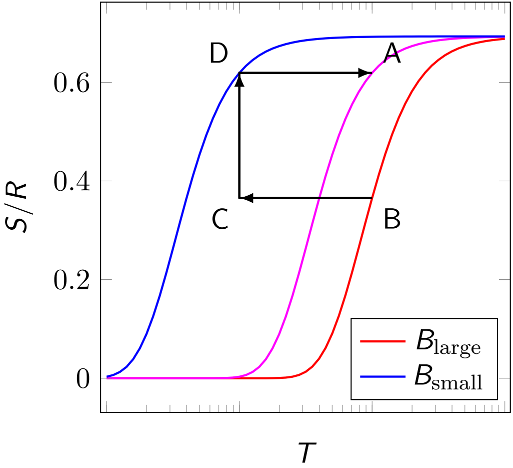
Adiabatic Demagnetization Refrigeration Principles

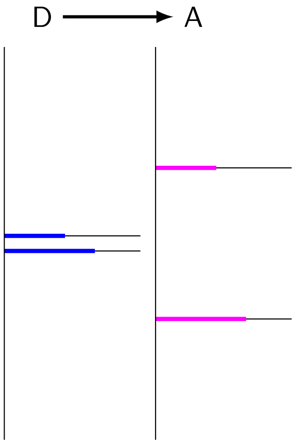




in space: isothermal $B \Downarrow$ lifts heat (grey area)

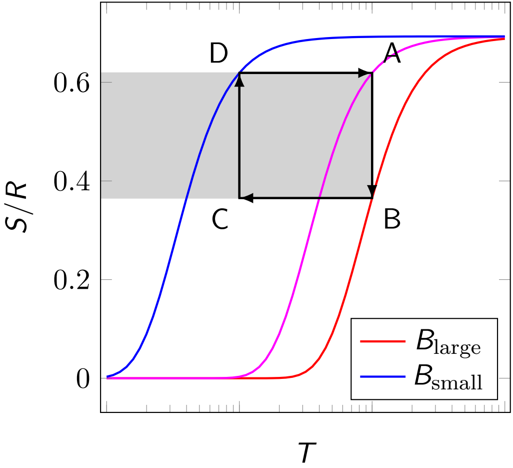
Adiabatic Demagnetization Refrigeration Principles

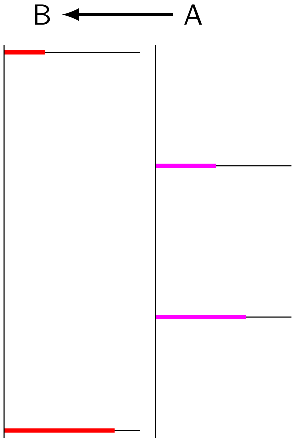




in space: adiabatic $B \Uparrow$ implies spin system $T \Uparrow$

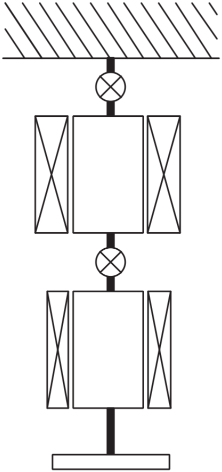
Adiabatic Demagnetization Refrigeration Principles



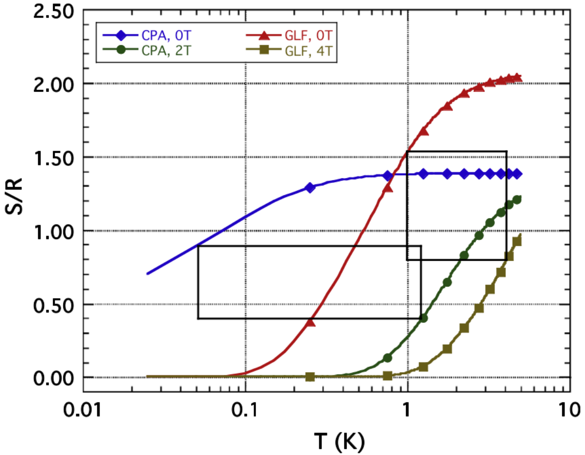


in space: isothermal $B \Uparrow$ dumps heat (grey area)

2-Stage Single-Shot ADR



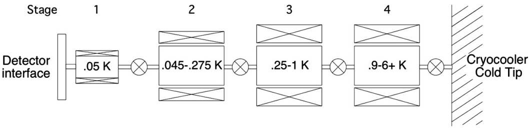
Shirron.Cryogenics.62.130



Shirron.Cryogenics.62.130

GLF demagnetization at $T = 1.0\,\mathrm{K}$ lifts heat from CPA magnetization at $T = 1.1\,\mathrm{K}$

Multi-Stage Continuous ADR

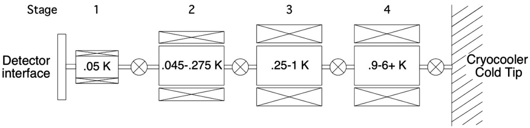


heat switches

- 1 superconductor
- 1 active gas gap
- 2 passive gas gap

Shirron.Cryogenics.62.130

Multi-Stage Continuous ADR



Stage	Refrigerant	B (T)	T_{high} (K)	T_{low} (K)	Mass (kg)
1	60 g CPA	0.1		0.05	0.5
2	100 g CPA	0.5	0.3	0.045	1.7
3	100 g CPA	1.5	1.3	0.25	2.4
4	65 g GLF	4.0	5	1.15	3.1

heat switches

- 1 superconductor
- 1 active gas gap
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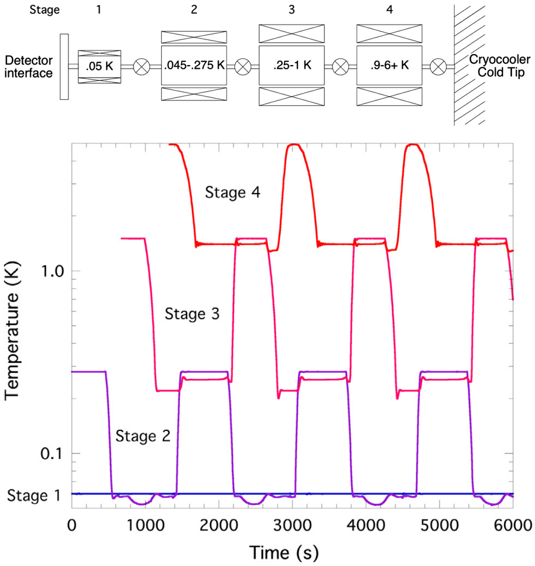
ramp B and switch $\dot{Q}$

- as fast as possible
- switch time is limit

Shirron.Cryogenics.62.130

Multi-Stage Continuous ADR



Shirron.Cryogenics.62.130

heat switches

- 1 superconductor
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ramp B and switch $\dot{Q}$

- as fast as possible
- switch time is limit

magnetic shielding

- active superconducting

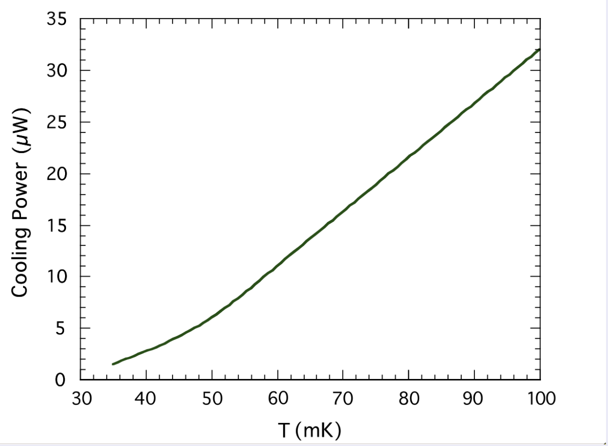
  Pourrahimi.Cryogenics.48.253

- passive ferromagnetic and superconducting

  Prouve.Cryogenics.64.201

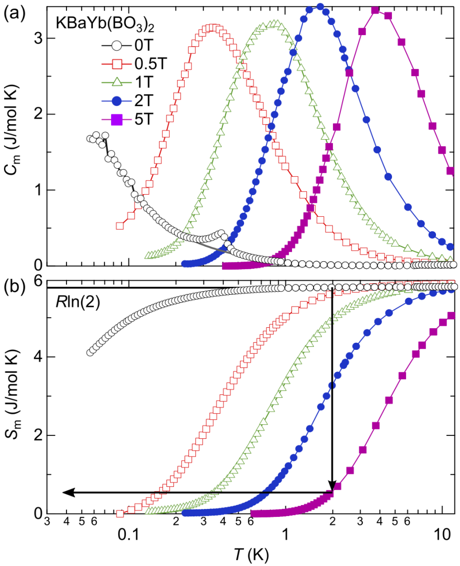
Multi-Stage Continuous ADR

experimental cooling power versus temperature



Shirron.Cryogenics.62.130

New Materials for Continuous ADR

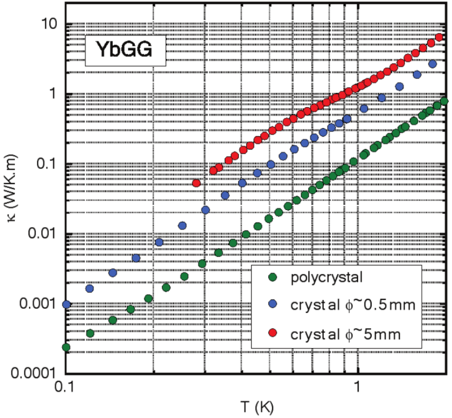


Tokiwa.CommunicationsMaterials.2.42

frustrated antiferromagnetism

- antiferromagnetic order is incompatible with triangular lattice
- replace paramagnetic salts
  - higher entropy density
  - insensitive to vacuum
  - insensitive to high T
  - not corrosive

New Materials for Continuous ADR



Brasiliano.Cryogenics.105.103002

$\kappa_{5\,\text{mm diameter}} \approx \kappa_{\text{Brass UNS C26000}}$

frustrated antiferromagnetism

- antiferromagnetic order is incompatible with triangular lattice
- replace paramagnetic salts
  - higher entropy density
  - insensitive to vacuum
  - insensitive to high T
  - not corrosive
  - better thermal contact
- more material research
- experts:
  - France: CEA-DSBT
  - USA: NASA

Outline

Conclusion: Technology Comparison

model	$T_{\min}$ mK	$\dot{Q}$ @ T µW @ mK	^{4}He
Oxford Kelvinox 400	< 7	400 @ 100	wet
Oxford Proteox 5mK900	< 5	25 – 850 @ 20 – 100	dry
Leiden CF-CS110-1500	7	1500 @ 100	dry
BlueFors XLD1000	8 – 10	450 – 500 @ 100	dry
NASA CADR	35 – 100	1.5 – 32 @ 35 – 100	both

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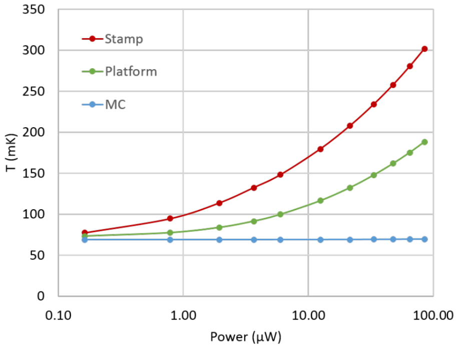
	dry DR	wet DR	DIY
outside space	large	small	any
configuration	fixed	fixed	any
vibrations	PTC+pumps	pumps	any
know-how	company	company	you

Conclusion: Technology Comparison



Liberadzka.Thesis.2019

NASA ADR has $\dot{Q} = 16\,\mu\mathrm{W}$ @ $T = 70\,\mathrm{mK}$: 6 times less than used

Conclusion: Technology Comparison

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CADR is sensitive to magnetic field

CADR may require control of stray fields

I extrapolate $\dot{Q}_{\mathrm{load}\ @\ 4\,\mathrm{K}} \approx (3-10)\,\mathrm{mW}$

lots of room for improvement

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