Hybrid nuclear-electronic order at 2 mK in the heavy fermion system $YbRh_2Si_2$

- Recent observation in $YbRh_2Si_2$:
  → at 2 mk: magnetic transition combined with onset of superconductivity

- Very unusual, mechanism unclear,
  - proposed to be hybrid nuclear-electronic order

- My own ideas on the origin of the 2 mK transition in $YbRh_2Si_2$

How can tiny nuclear moments induce a new electronic state in a lattice of strongly interacting, large moment Kramers ions

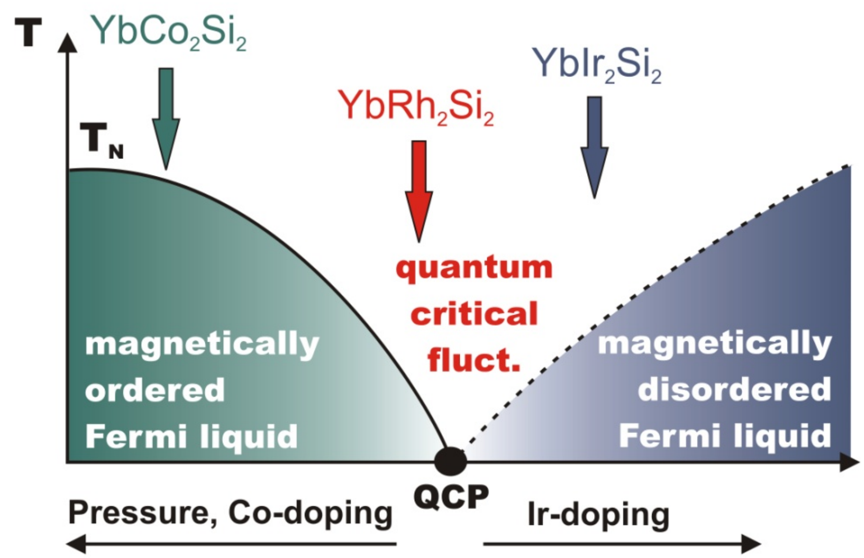
- Discussion with and strong support from Manuel Brando + Alexander Steppke (MPI – CPfS)

- Interesting and constructive discussion with Q. Si, E. Schubert, and F. Steglich

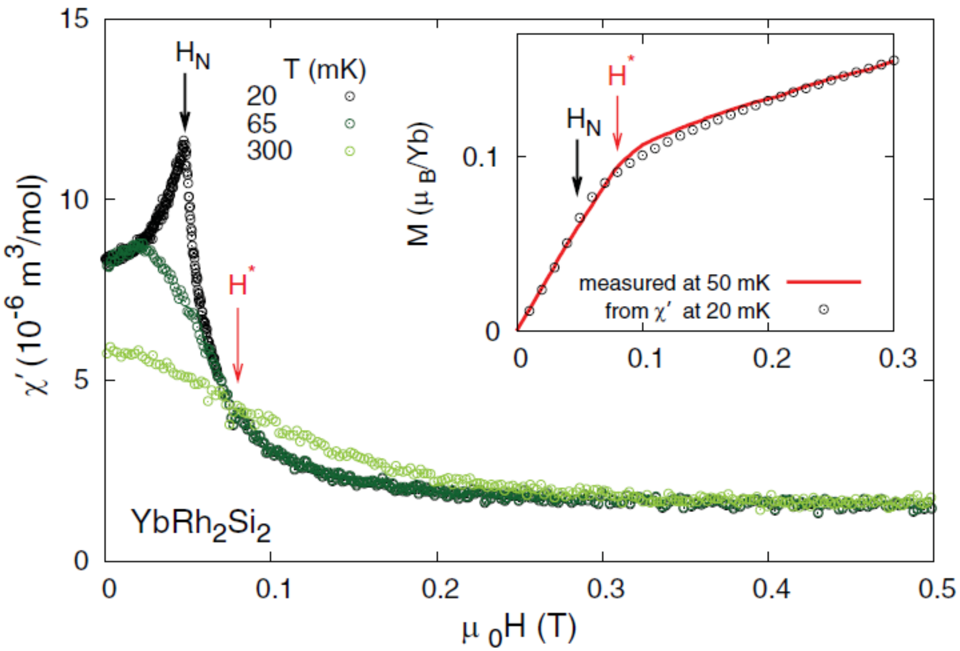
The heavy fermion system $YbRh_2Si_2$

$YbRh_2Si_2$: Prominent system in the field of QCP

- Heavy Fermion system, Kondo scale $T_K \approx 20$ K
  - * AFM order at very low T: T_N = 70 mK,
  - $\rightarrow$ very close to the AFM QCP
  - * QCP induced by small magnetic field or small negative pressure



ac susceptibility and magnetization



M. Brando et al., Phys. Stat. Sol. 3 (2013) 485

AFM order at T_N = 70 mK

- Large λ-type anomaly in C(T) at 70 mK
  - entropy: $S(T_N) \cong 3\%$ Rln2 (Kondo screening)
- In-plane field (strong XY anisotropy):
  - Peak in χ(T) at T_N
  - Kink in magnetization at B_c = 0.06 T
- Size of ordered moment: - μSR: 0.002 μ_B
- AFM structure still unknown

New transition at 2 mK

- E. Schubert et al., Science 351 (2016) 485
- Measurements:
  - dc magnetization with SQUID
  - ac susceptibility with SQUID and with conventional coil technique

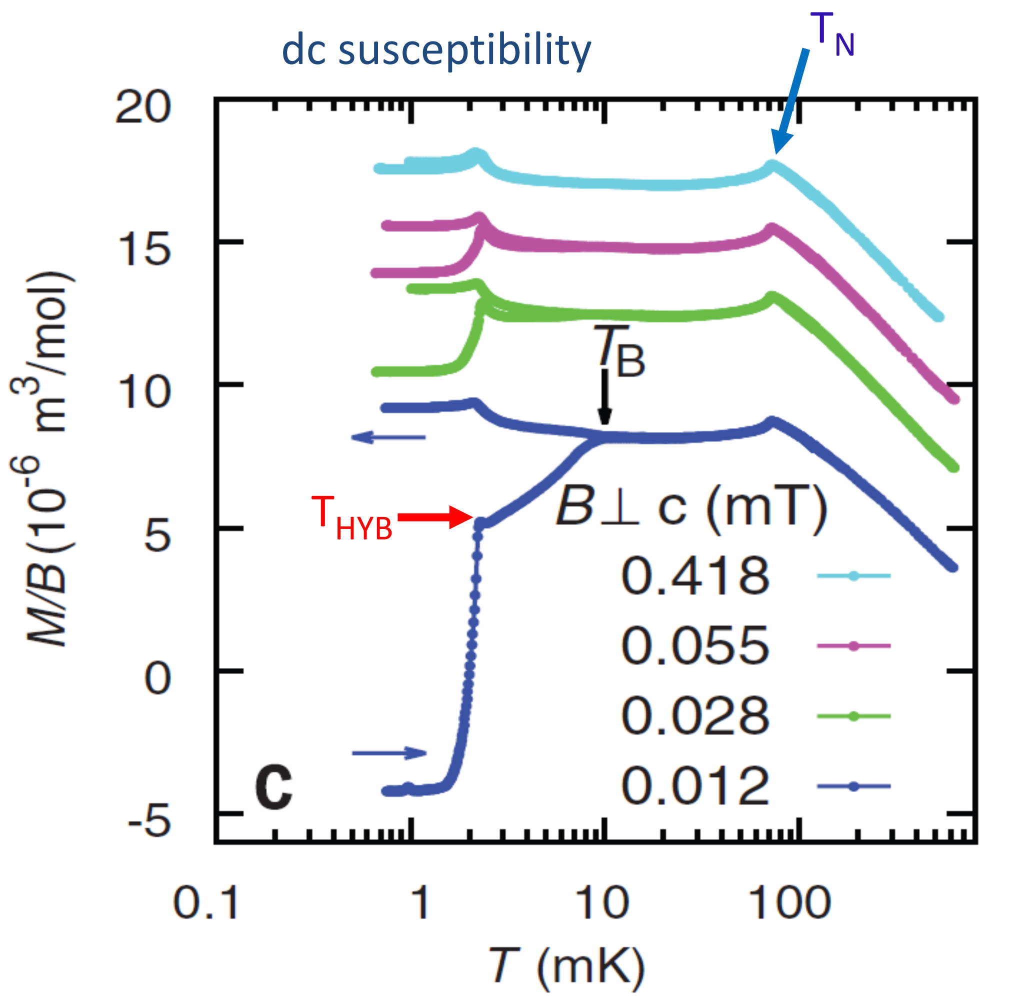
→ clear and sharp anomaly at T_{HYB} = 2 mK

→ opening of a hysteresis below T_B = 10 mK

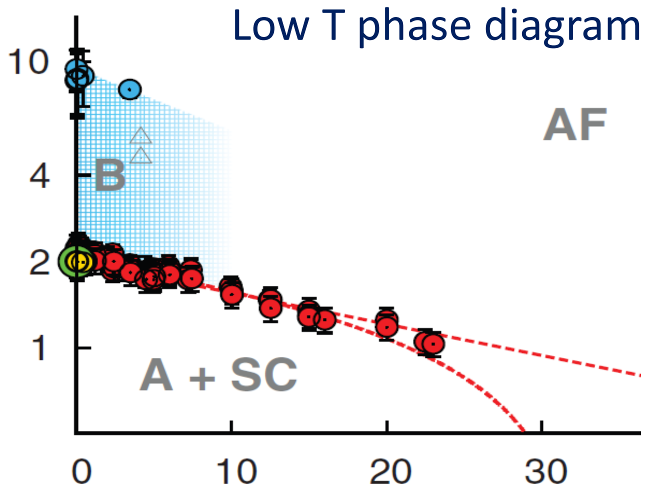
→ zfc signal at very low field diamagnetic

→ strong suppression with increasing field

dc susceptibility



Low T phase diagram

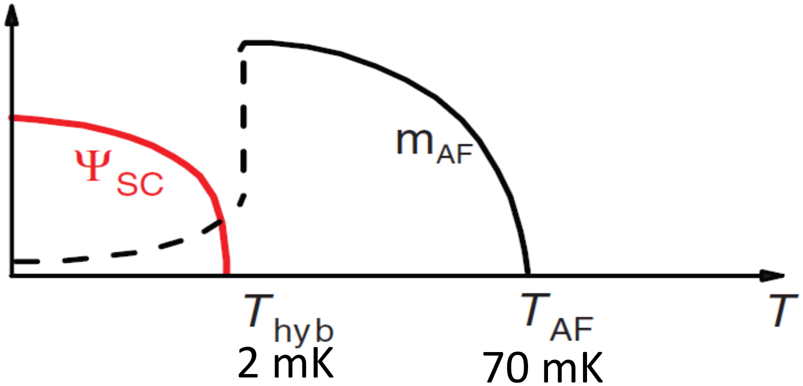


⇒ clear evidence for a magnetic transition at T_{HYB}

⇒ preliminary evidence for onset of superconductivity

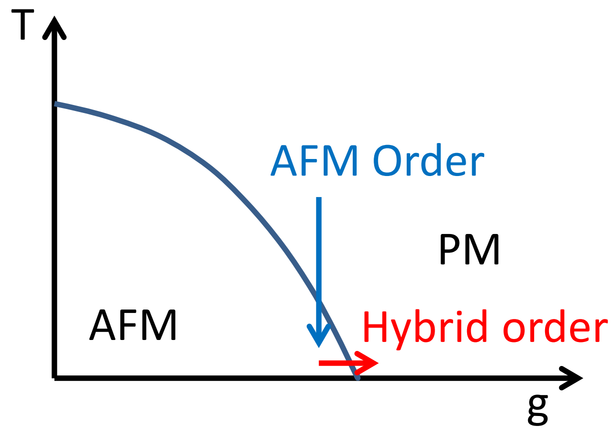
- Superconductivity confirmed in recent noise resistivity measurements by J. Saunders et al.

Initially proposed scenario



Scenario proposed in E. Schuberth et al.:

- At 2 mK onset of hybrid nuclear/electronic order
  - → suppress 4f AFM magnetic order
  - → results in crossing QCP towards the PM regime
  - → induces superconductivity
- Nuclear order parameter: primary order parameter of hybrid order
  - electronic component of hybrid order undefined
- Analyzed using 3 components Landau type model
  → 9 parameters: - 1 parameter fixed: hyperfine coupling
  - 2 constrains: T_{AF} and T_{HYB}



⇒ Huge number of free parameters: - parameters can be tuned to support proposed scenario
- but many other scenario can be modelled as well

⇒ Ad hoc scenario! - very speculative - model has only limited significance

- only weak connection to properties of $YbRh_2Si_2$ - some problematic assumptions

⇒ met strong skepticism

Need for a more stringent approach with a better connection to specific properties of $YbRh_2Si_2$

Here: alternative approach: let´s start from $YbRh_2Si_2$

- Empirical approach

- discuss hyperfine coupling in Yb

- Single out very peculiar properties of $YbRh_2Si_2$

→ Because of these peculiar properties, nuclear moments are expected to interfere with electronic moments at $T \approx 2$ mK

⇒ New model: • coupled nuclear – electronic transition
• but 4f moments increase below T_{HYB} instead of decreasing

- Analyze possible origin for peculiar properties of $YbRh_2Si_2$

Nuclear versus electronic entropy

Electronic entropy

- Analysis of C(T, B) data

→ Reliable map of Entropy S(T,B)

→ reasonable approximation below 30 mK

⇒ At 30 mK $S_{elec} = 0.01$ Rln2

⇒ At 3 mK $S_{elec} = 0.001$ Rln2

Yb nuclear entropy

- ^{171}Yb I = 1/2 abundance 14 %
  ^{173}Yb I = 5/2 abundance 16 %

- Analysis of C(T) data
  + Estimation of quadrupolar splitting
  → Yb-Nuclear Entropy: $S_{nuc\text{-}Yb}(T)$

⇒ At 30 mK $S_{nuc\text{-}Yb} = 0.56$ Rln2

⇒ At 3 mK $S_{nuc\text{-}Yb} \cong 0.5$ Rln2

⇒ At 3 mK: Yb-nuclear entropy >>>> electronic entropy

- Strong coupling between Yb-nuclear moment and electronic Yb - 4f moments

→ any change in 4f states shall affect splitting of Yb-nuclear magnetic levels

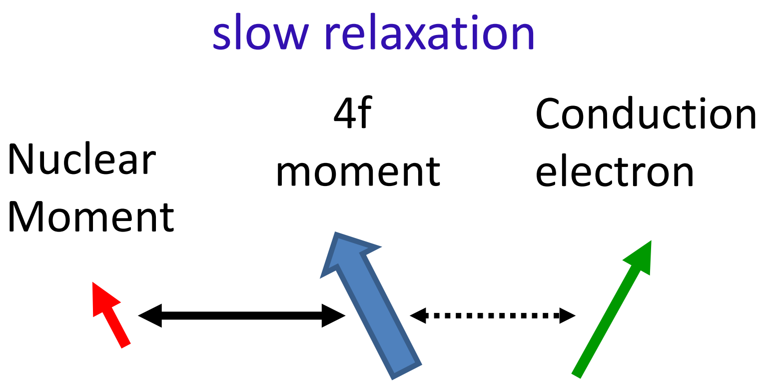
- 2 mK transition: anomaly in $\chi(T)$ → 4f moments are affected → nuclear moments affected too

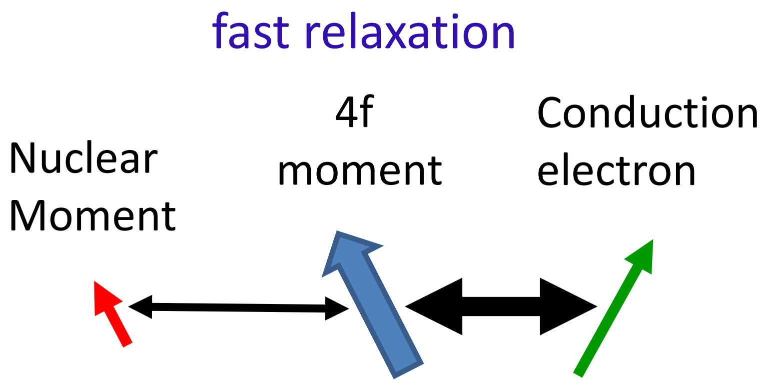
⇒ Regarding entropy: 2 mK transition is completely dominated by nuclear contribution

⇒ Nuclear moments are strongly involved in 2 mK transition

Hyperfine coupling in Yb

- Magnetic rare earth elements: very strong hyperfine coupling
- Hyperfine coupling in Yb completely dominated by effect of 4f-shell
- Two different regimes: “fast” and “slow” relaxation regimes





- $YbRh_2Si_2$: strong Kondo interaction $\rightarrow$ “fast relaxation regime” - confirmed by experiments

$\Rightarrow$ 4f moments arrange according to RKKY and Kondo interactions (don´t care about nuclear m)

$\Rightarrow$ Yb nuclear moment arrange according to static dipolar + quadrupolar field produced by 4f el.

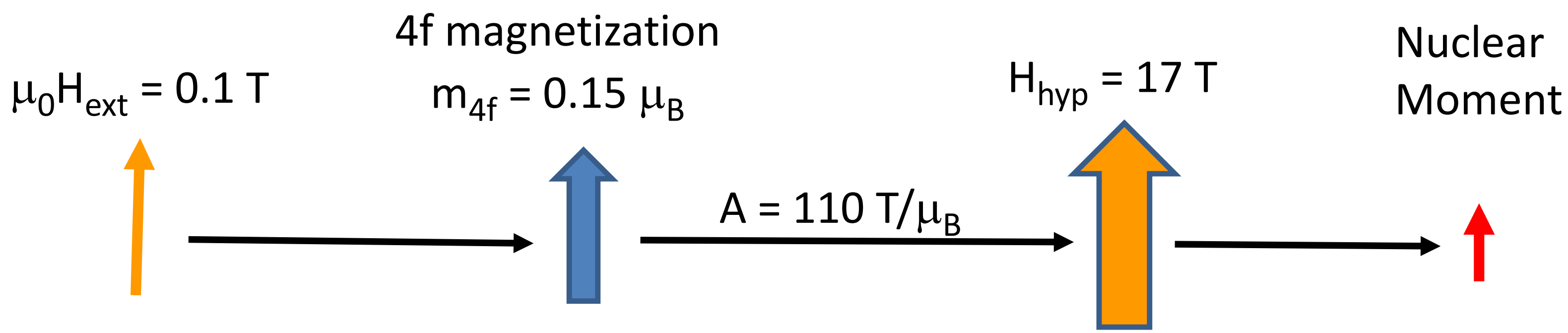
Hyperfine coupling in fast relaxation regime

$\Rightarrow$ Nuclear moment in dipolar hyperfine field H_{hyp}

- $H_{hyp} \propto$ on-site static 4f polarization m_{4f} : $H_{hyp} = A * m_{4f}$
- with $A \cong 110$ T/μ_B (theory + experiment)

• Example $YbRh_2Si_2$ ($T < 200$ mK):

Apply a small external in-plane field



$\rightarrow H_{hyp}$ factor 170 larger than H_{ext} $\Rightarrow$ only on-site static 4f polarization matters

Problems for nuclear order induced transition

- Fast relaxation regime: $\rightarrow$ 4f moments arrange according to electronic interactions
  $\rightarrow$ 4f moments define state of nuclear moments, not the inverse

- Further problem for nuclear order on its own
  - only 32% of Yb nuclei carry a nuclear moment

  $\rightarrow$ 68 % of Yb nuclei inactive

  - Two different types of nuclear moments: - different I, - different moment size
    - coupling of I and J: AFM in ^{171}Yb, FM in ^{173}Yb

  $\Rightarrow$ 32 % active nuclear moments, with two different kinds of properties, are statistically distributed in the lattice

  $\Rightarrow$ Nuclear order on its own would certainly be a short range, spin glass type
  $\rightarrow$ No sharp transition

- But regarding entropy nuclear moments are dominant

How to overcome this problem?

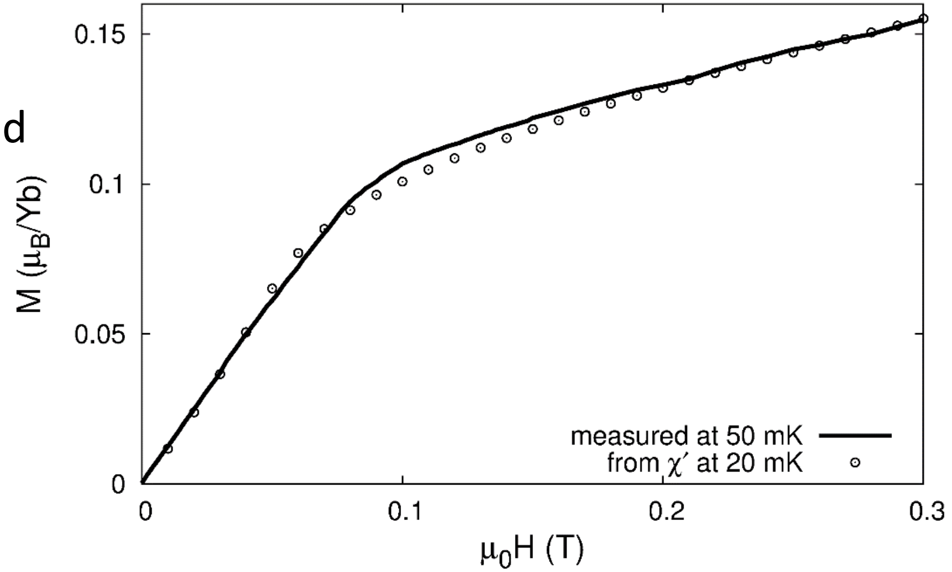
$\rightarrow$ Electronic order is primary order parameter of hybrid state

$YbRh_2Si_2$: extremely small value of AFM ordered moment Very peculiar field dependence of local 4f static moment

- In-plane magnetization of $YbRh_2Si_2$
  - M(H) increases linearly with H until $H = H_c$:
  - $\rightarrow$ as expected for a standard AFM
  - ordered moments rotate towards external field

Low field in-plane magnetization of $YbRh_2Si_2$

M. Brando et al., Phys. Stat. Sol. 3 (2013) 485



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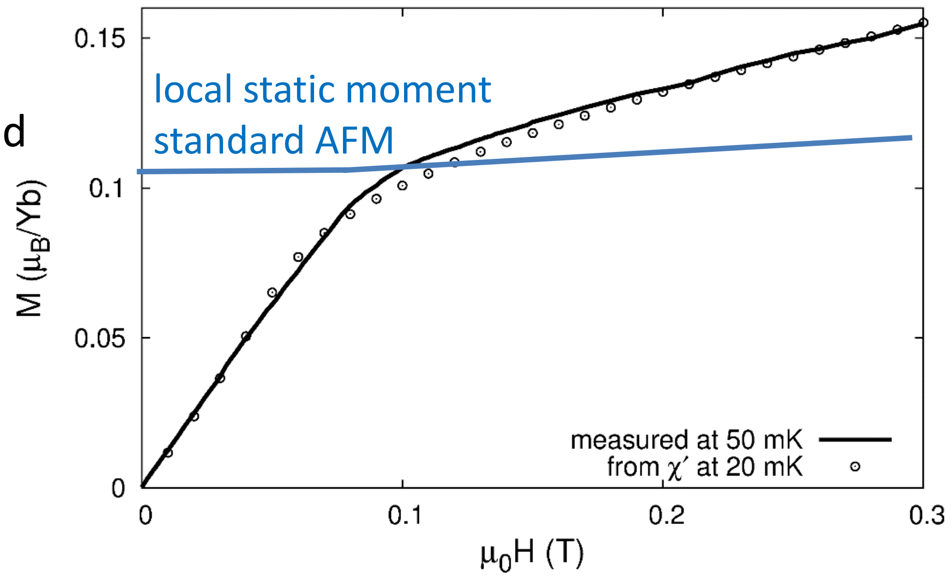

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! $YbRh_2Si_2$: nuclear specific heat:
local static moment decreases strongly below H_c!

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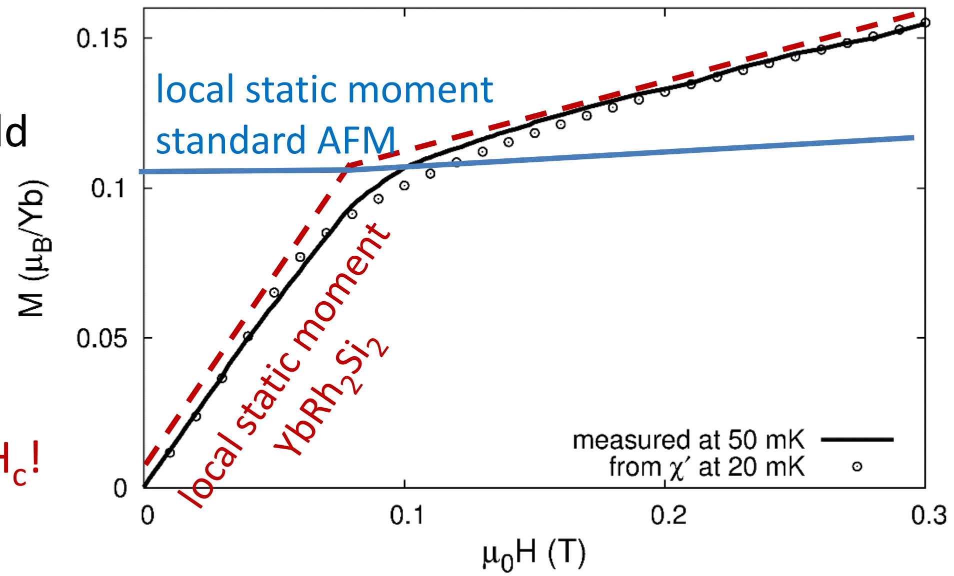
M. Brando et al., Phys. Stat. Sol. 3 (2013) 485



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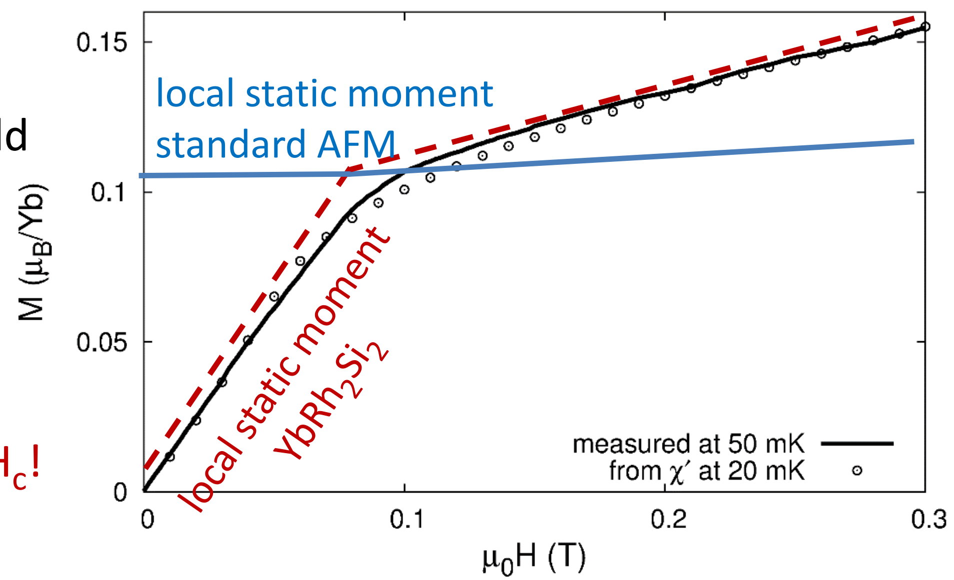
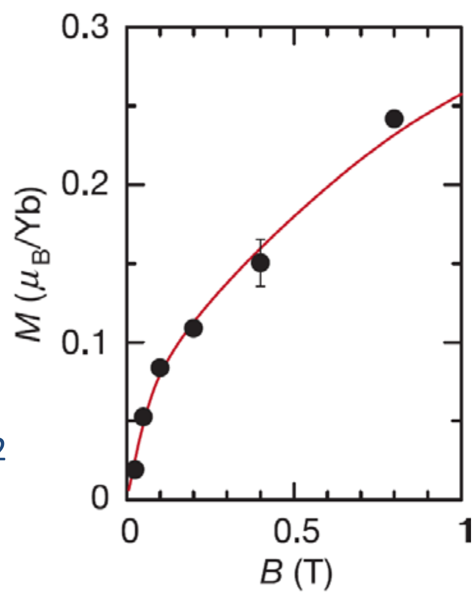


Comparison:
bulk magnetization and m_{4f} deduced from $C_{nuclear}$

$YbRh_2(Si_{0.95}Ge_{0.05})_2$



- $H < H_c$: m_{4f} follows bulk magnetization $M(H)$

- μSR results: K. Ishida et al., 2003

$\Rightarrow$ $T < T_N$: increase in relaxation rate Λ very small

$\Rightarrow$ tiny ordered moment $m_{AFM}(H = 0) \approx 0.002\ \mu_B$ much smaller than saturation moment

Looking at energies: a first clue

Extremely small AFM ordered moment: $m_{AFM}(B=0) \approx 0.002\ \mu_B/\text{Yb}$

Tiny field $B_c = 0.07$ T sufficient to induce much larger saturation moment $m_{sat} = 0.10\ \mu_B/\text{Yb}$

$\rightarrow$ Energy required to induce a larger moment is very small: $\Delta Esat_{mag} = 1/2 * m_{sat} * B_c$

$\Rightarrow \Delta Esat_{mag}/k_B = 2.3$ mK

- Increase in static local moment $\rightarrow$ increase in nuclear polarization energy

$\Delta Esat_{nuclear} = n * \Delta H_{hyp} * m_{nucl}$

$n = 0.30$: proportion of Yb with a nuclear moment

$\Delta H_{hyp} = A_{hyp} * \Delta m_{sat} = 11$ T

$m_{nuclear} = 0.6\ \mu_N/\text{Yb}$: Mean Value ($^{171}\text{Yb} + {}^{173}\text{Yb}$)

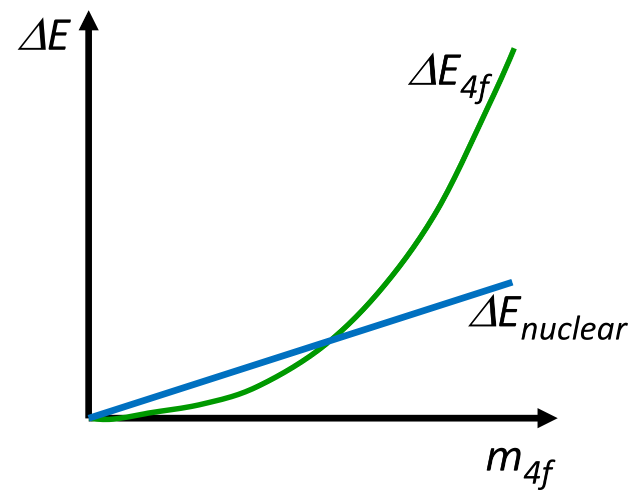
$\Rightarrow \Delta Esat_{nuclear}/k_B = 0.72$ mK

$\Rightarrow$ Gain in nuclear polarization energy: same order of magnitude as 4f polarization energy

Can nuclear polarization energy replace external field?

- Energy required to increase the electronic static local polarization: $\propto (m_{4f})^2$
- Gain in nuclear polarization energy: $H_{HYP} \propto m_{4f}$ $\rightarrow \Delta E_{nuclear} = \propto m_{4f}$

$\Rightarrow$ At low T nuclear polarization energy wins



- How large shall be m_{4f} induced by hyperfine coupling at T = 0 ?

  - simple approximation using measured magnetization and hyperfine coupling

  $\Rightarrow$ induced moment: $m \cong 0.02\ \mu_B$/Yb: a factor of 10 larger than ordered moment at 30 mK!

$\Rightarrow$ At T = 0, ignoring further possibilities, hyperfine coupling would lead to an increase of the ordered moment by one order of magnitude!

$\Rightarrow$ in $YbRh_2Si_2$, AFM state with very low ordered moment is inherently unstable at very low T against an increase of the 4f moment due to nuclear polarization!

Instability towards larger moment visible in low T susceptibility

- Simple thermodynamic model: 4f moments + hyperfine coupled nuclear moments
- Free Energy: $G(T, B) = G_{el}(T, B) + G_{nucl}(T, H_{hyp})$ $\rightarrow$ $M(T) = \partial G/\partial B$

$\rightarrow$ $\chi(T) = \chi_{4f\text{-}0} + 1 / T * K * (\chi_{4f\text{-}0})^2$

- $\chi_{4f\text{-}0}$: 4 f susceptibility without nuclear coupling
- $K = n * (A_{hyp} * m_{nuc})^2$

$\Rightarrow$ At low T, 4f polarization enhanced due to hyperfine coupling $\rightarrow$ Curie-Weiss upturn in $\chi(T)$

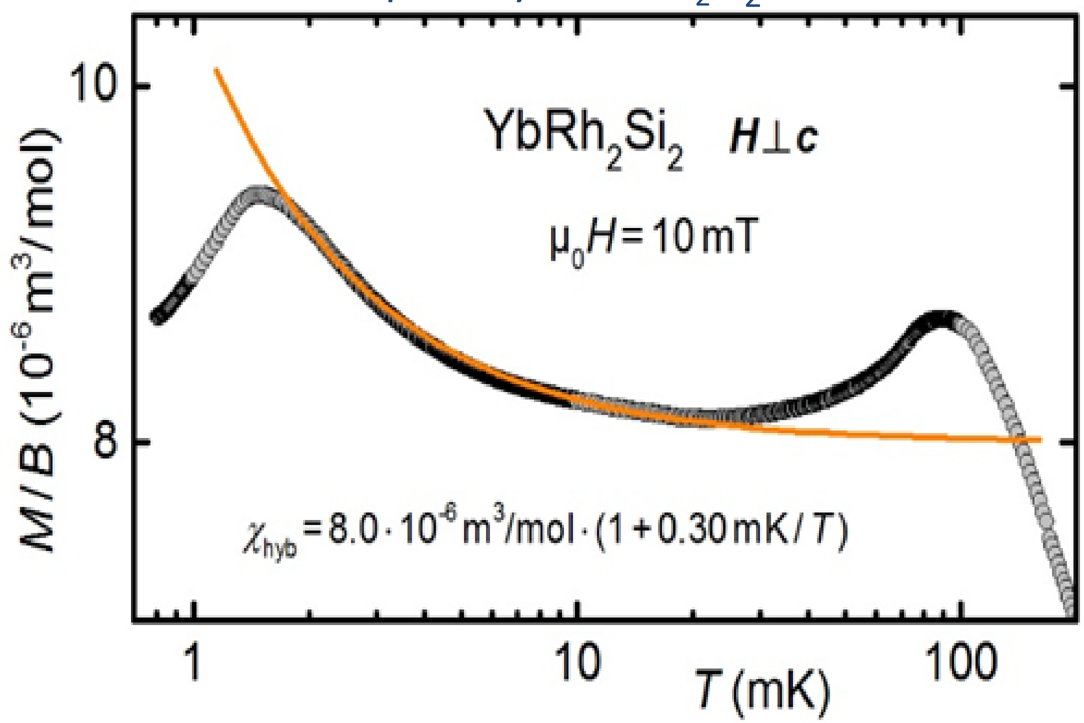
! same result as for hyperfine enhanced Van Vleck paramagnets

- No free parameter **!**
  - $\chi_{4f\text{-}0}$ fixed by $\chi(T)$ above 10 mK

$\rightarrow$ Reproduces very nicely increase in $\chi(T)$ for $T_{HYB} < T < 30$ mK

$\Rightarrow$ Direct evidence for instability towards states with larger ordered 4f moment

Susceptibility of $YbRh_2Si_2$ at low T



Energy landscape of electronic magnetic states in $YbRh_2Si_2$

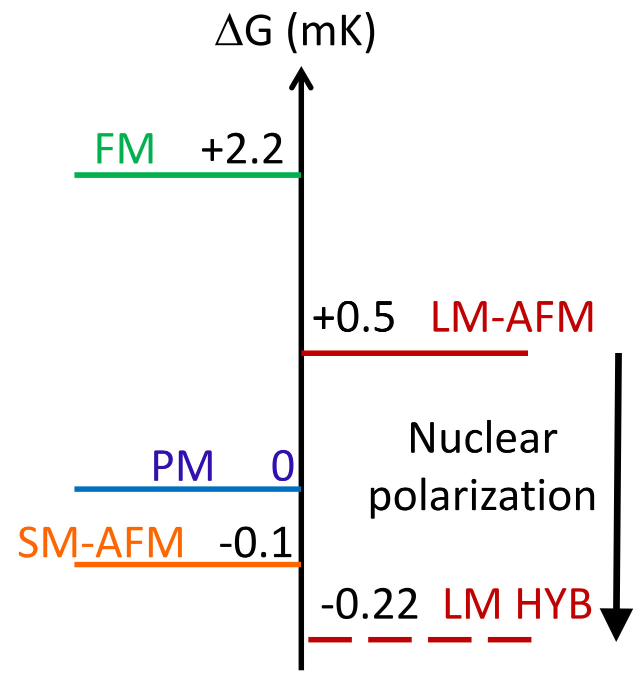
- Magnetization + specific heat → free energy of some relevant states

- Energy in k_b, zero is "T = 0" paramagnetic state

- Small moment AFM state (SM-AFM) formed at 70 mK
  → Condensation energy $\Delta G \cong -0.1$ mK

- FM state with "large" ordered moment = 0.1 μB
  → $\Delta G \cong +2.2$ mK

- In $YbRh_2Si_2$: AFM order more stable than FM order
  → likely an AFM state with large ordered moment
  $m_{4f} \approx 0.1\ \mu_B$ (LM-AFM) in-between FM and SM-AFM state



⇒ larger ordered moment → larger nuclear polarization energy
⇒ stabilizes LM-AFM at low T

- Transition temperature?

⇒ strongly defined by achievable nuclear Zeeman splitting Δ_{ZM}

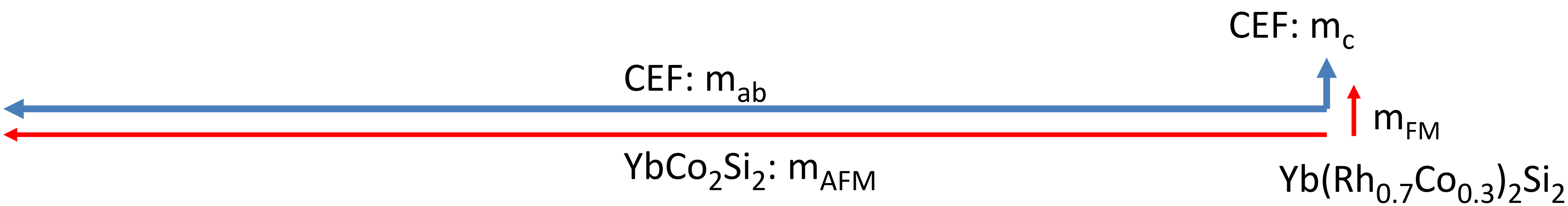
→ *T* has to be sufficiently low to only populate lowest nuclear Zeeman level

→ $m_{4f} \approx 0.1\ \mu_B$ → $\Delta_{ZM} = 4.8$ mK ⇒ T_{hyb} of the order of 1 mK

Possible origin for tiny AFM ordered moment and for peculiar field dependence of m_{4f}

- Crystal electric (CEF) in $YbRh_2Si_2$ → huge anisotropy, almost pure XY behavior
- CEF ground state doublet: - very large in-plane moment $m_{ab} = 1.8\ \mu_B$
  - tiny z-axis moment $m_c \leq 0.08\ \mu_B$

⇒ General belief: AFM ordered moment oriented in-plane
(but no experimental proof!)



But very surprising results in the alloy $YbRh_2Si_2$ - $YbCo_2Si_2$

- $YbCo_2Si_2$: ($T_K << T_{RKKY}$) → stable local 4f moment system
- AFM state below T_N = 1.7 K: - large ordered moment - oriented in-plane (as expected)
- But for 0.25 < x < 0.6: - FM state - ordered moment along c axis (a mystery!)
- B-T phase diagram for x < 0.25: → c component also close to pure $YbRh_2Si_2$

AFM moment along c in pure $YbRh_2Si_2$ too?

- already suggested in PhD Thesis of Jeroen Custers (TU Dresden, 2004)

$\rightarrow$ would explain tiny size of ordered moment:

- Size of Kondo screening? - m_{sat} = 0.12 μ_B in a-b-plane factor 15 smaller than in-plane CEF m_{sat}

  $\rightarrow$ Kondo screening reduces CEF moment by a factor 15

  - compatible with entropy $S(T_N)$ = 0.03 Rln2

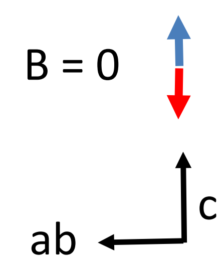
$\Rightarrow$ moment along c direction expected to be reduced by a factor 15 too

  $\rightarrow$ $m_c \leq 0.08\ \mu_B\ /15\ \ \leq 0.005\ \mu_B$

$\Rightarrow$ Provides simple explanation for peculiar field dependence of m_{4f}

- Increase of local static moment $m_{4f}(B)$ for in-plane field:

  $\rightarrow$ rotation from c-axis (small moment) to a-b-plane (large moment)



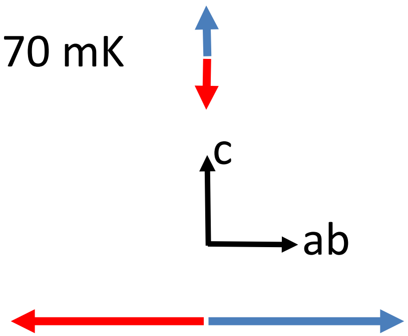
- Then very likely that
  - AFM state with large in-plane ordered moment

  is close in energy to - AFM ground state with small c ordered moment

suggests following scenario for 2mK transition

- Below T_N = 70 mK, AFM moments order along c
- Transition at 2 mK: upon cooling, transition
  from a - c oriented, small moment AFM state
  to a - in-plane oriented large moment AFM state
  - stabilized by the larger nuclear polarization

2 mK < T < 70 mK

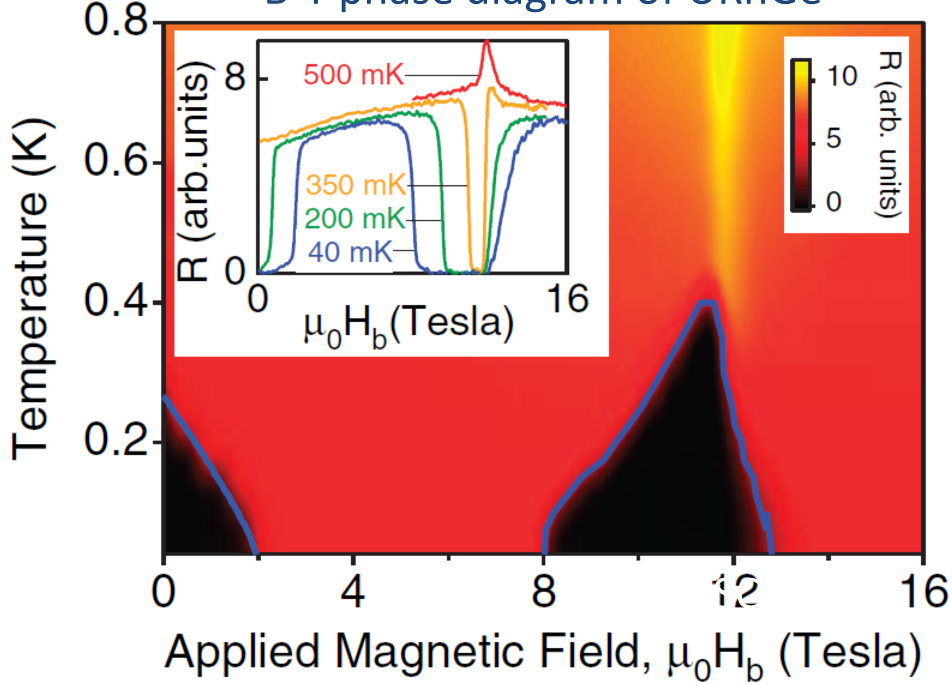


T < 2 mK

→ Superconductivity not connected with AFM–PM QCP
  - but with critical point associated to a change of magnetic structure

- relation to reentrant superconductivity in URhGe?
  - Large field along hard axis
  → Moments switch toward hard axis
  → Superconductivity with enhanced Tc

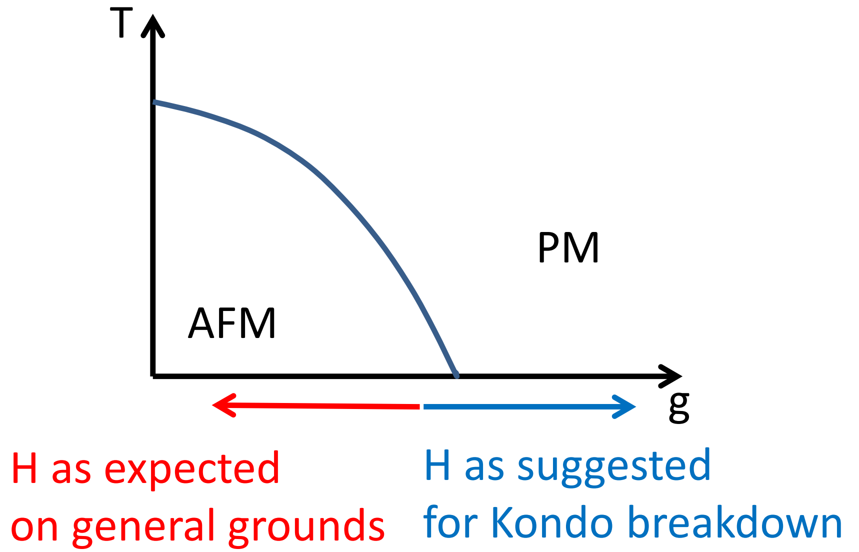
B-T phase diagram of URhGe



F. Lévy et al., Science 309 (2005) 1343

Field induced Kondo breakdown in $YbRh_2Si_2$???

- Theoretical calculations for Kondo breakdown scenario:
  - always as a function of hybridization
  - no calculation as a function of magnetic field H



- In presentation/papers:
  - suggestion: H ≅ increasing hybridization

  ⇒ A priory wrong! magnetic field drives Kondo systems towards localized state

  ⇒ In general: H ≅ decreasing hybridization

→ Claim for field induced Kondo breakdown needs some additional mechanism

- e.g. like FM Ising system in a transverse field: → increasing H reduces static polarization
- yet no proposition for an appropriate mechanism in $YbRh_2Si_2$

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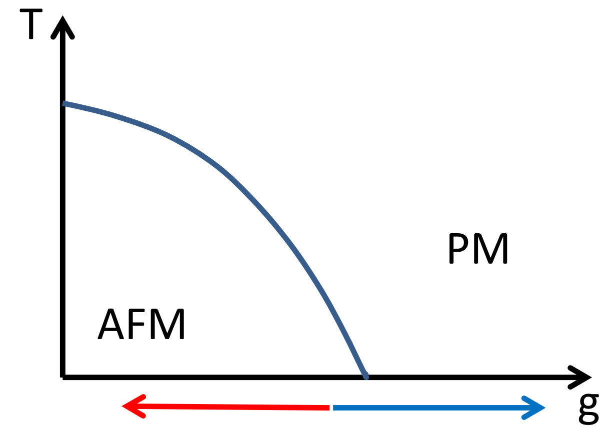


Field effect as deduced from nuclear C(T)

Field effect as needed for Kondo breakdown

→ Claim for field induced Kondo breakdown needs some additional mechanism

- e.g. like FM Ising system in a transverse field: → increasing H reduces static polarization
- yet no proposition for an appropriate mechanism in $YbRh_2Si_2$

- $YbRh_2Si_2$: nuclear specific heat ⇒ static 4f polarization continuously increases with in-plane H !
  - same as for Co doping or isostatic pressure: → in-plane H ≅ decreasing hybridization

  ⇒ in-plane magnetic field continuously shift $YbRh_2Si_2$ towards a polarized localized state

  ⇒ very strongly question the possibility for a field-induced Kondo breakdown

⇒ no sound theoretical basis for claiming a field induced Kondo breakdown in $YbRh_2Si_2$ (H II ab)

Summary

- $YbRh_2Si_2$ → two very peculiar properties of AFM state formed at T_N = 70 mK:
  - an extremely small value of the ordered moment $m_{4f\_AFM} \approx 0.002\ \mu_B$
  - tiny external field is sufficient to induce a much larger local moment $m_{4f} \approx 0.10\ \mu_B$

⇒ both properties makes this AFM state inherently unstable against a large moment state stabilized by nuclear polarization at ≈ 1 mK

⇒ 2 mK transition: transition from - a small ordered moment AFM state
to - a large ordered moment AFM state

- stabilized by nuclear polarization energy

2 mK transition: transition to a smaller value of the ordered 4f moment?

- Hyperfine coupling: $YbRh_2Si_2$ is in the fast relaxation regime
  - $\rightarrow$ problem reduces to nuclear moment in hyperfine field produced by 4 f moment
  - $\rightarrow$ equivalent to paramagnetic moment in external field

- Entropy S(B, T) of PM moment in external field: universal function of T/B,
  - $\rightarrow$ monotonously increasing with T/B

- For nuclear system: $B = H_{HYP} \propto m_{4f}$
  - $\rightarrow$ Entropy of nuclear system is a function of T/m_{4f}, monotonously increasing with T/m_{4f}

- Because $S_{nuclear}(T) >>> S_{elec}(T)$ $\rightarrow$ $S_{nuclear}$ has to decrease below $T_{HYB} = 2$ mK

$\rightarrow$ therefore T/m_{4f} has to decrease below T_{HYB}

$\rightarrow$ m_{4f} cannot decrease faster than T

- Experimental evidence for a peak in C(T) at T_{HYB}, $\rightarrow$ significant reduction of S_{total}

$\Rightarrow$ m_{4f} has to increase below T_{HYP}

$\Rightarrow$ Transition at 2 mK cannot be associated with a transition from a large ($T > T_{HYB}$) to a small ($T < T_{HYB}$) 4f ordered moment AFM state

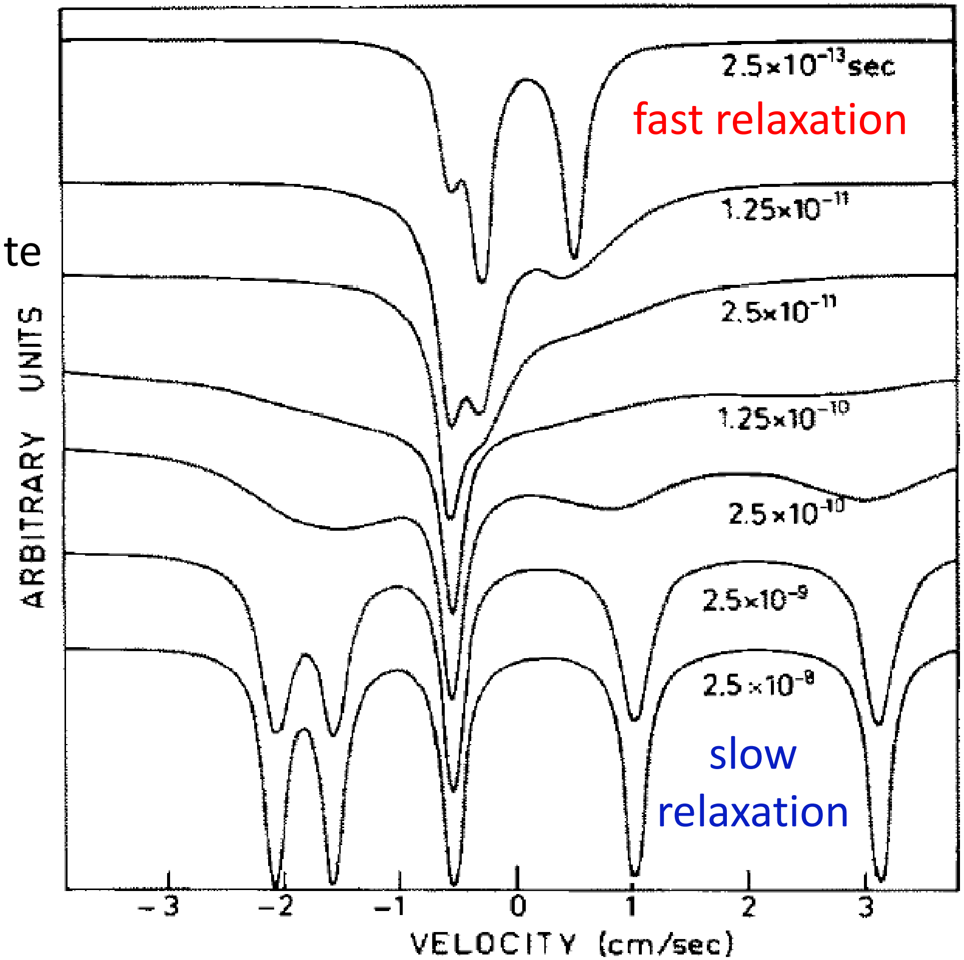
Slow or fast relaxation regime in Mößbauer spectroscopy

- Mößbauer Spectroscopy: active isotope is ^{170}Yb
  - Ground state: I = 0,
  - but excited state at 84 keV: I = 2
- Case A): "fast relaxation"
  - → I = 2 system in an external field
  - → in paramagnetic case only quadrupol field
    - quadrupol field depends on CEF ground state
- Case B): "slow relaxation"
  - → F = I + J = 2 + 1/2 = 5/2 (J = 1/2: CEF ground state doublet)
  - → Hyperfine coupling splits F multiplett (even at B = 0)
    - splitting dependent on CEF ground state

⇒ Slow or fast: very different spectra

Calculated Mößbauer spectra for paramagnetic Yb and large CEF anisotropy

I. Nowik, S. Ofer, J. Phys. Chem. Solids 29 (1968) 2117



Mößbauer on $YbRh_2Si_2$: fast relaxation regime

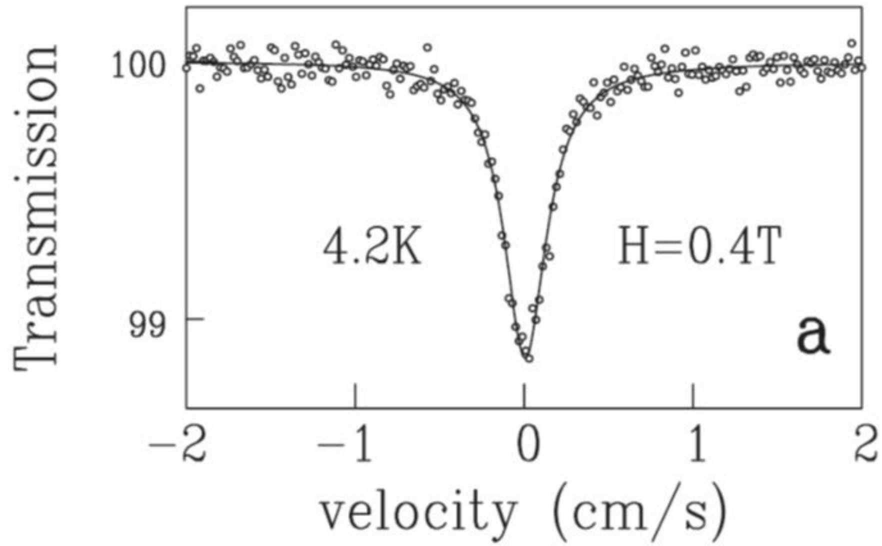
- Slow or fast: very different Mößbauer spectra
- Experiments: - G. Knebel et al.,

⇒ Single line, slightly broadened

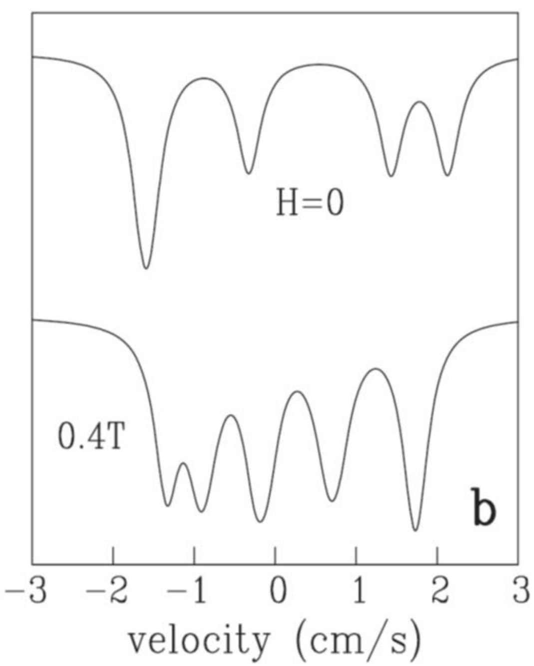
- J. Plessel et al., PRB 67 (2003) 18403

⇒ Similar result at 1.3 K

Mößbauer spectra (G. Knebel et al.)
J. Phys. Soc. Jpn. 75 (2006) 114709



Calculation for slow relaxation regime
with CEF of $YbRh_2Si_2$ (G. Knebel et al.)



⇒ Exp. results incompatible with slow relaxation regime

⇒ Exp. results in agreement with fast relaxation regime

- Quadrupol moment of Γ^7 CEF ground state proposed for $YbRh_2Si_2$ very small

→ Expected quadrupole splitting < natural line width

→ single line expected

Fast relaxation regime expected from large Kondo scale $T_K \cong 20$ K

Small or large Fermi surface in $YbRh_2Si_2$?

- Our ARPES results (K. Kummer et al., PRX 5, 011028 (2015)
  → Large fermi surface at B = 0 for 1 K < T < 100 K

  → strong controversy: - some parts of the community: cannot be !
  - other parts of the community: as expected !

- Recent STM results (S. Seiro, S. Wirth, unpublished, presented by S. Wirth at the ICM 2015)
  ⇒ at 300 mK, no significant changes in STM spectra for 0 < H < 9 T (across H*)

- general consensus: $YbRh_2Si_2$: at H > H* → large FS

- same STM spectra at H = 0 and at H = 9 T >> H*
  → large FS at T = 300 mK, B= 0 too

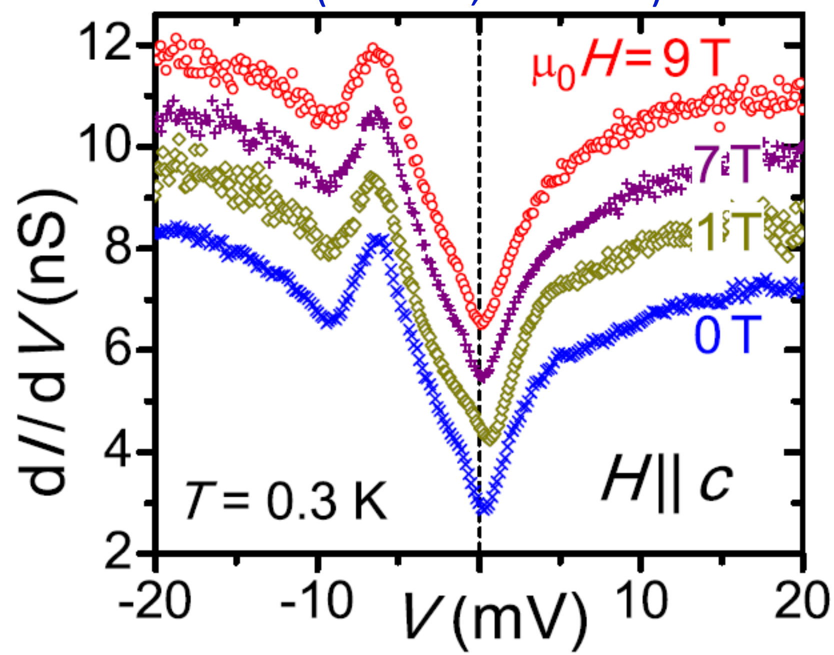
  → confirms our conclusions from ARPES

⇒ Large FS is present in a large H-T region completely enclosing the AFM state

⇒ In disagreement with original phase diagram drawn for Kondo breakdown scenario

⇒ supports SDW scenario

Field dependent STM spectra
(S. Seiro, S. Wirth)



Energy landscape E($m_{ordered}$, $Q_{ordered}$) in $YbRh_2Si_2$

b) paramagnetic versus AFM state

- Energy difference between AFM and PM state? = condensation energy of AFM state
- Can be estimated from specific heat data: → $\Delta G = -\iint_0^{TN} (C_{AFM}(T) - C_{PM}(T))/T * dT^2$

 - $C_{AFM}(T)$: experimental data
 - $C_{PM}(T)$: reasonable estimation using conservation of entropy at T_N and results for 5 % Ge-doped $YbRh_2Si_2$

→ $\Delta G = f * T_N^2 * (\Delta C_{MF}/T_N)$

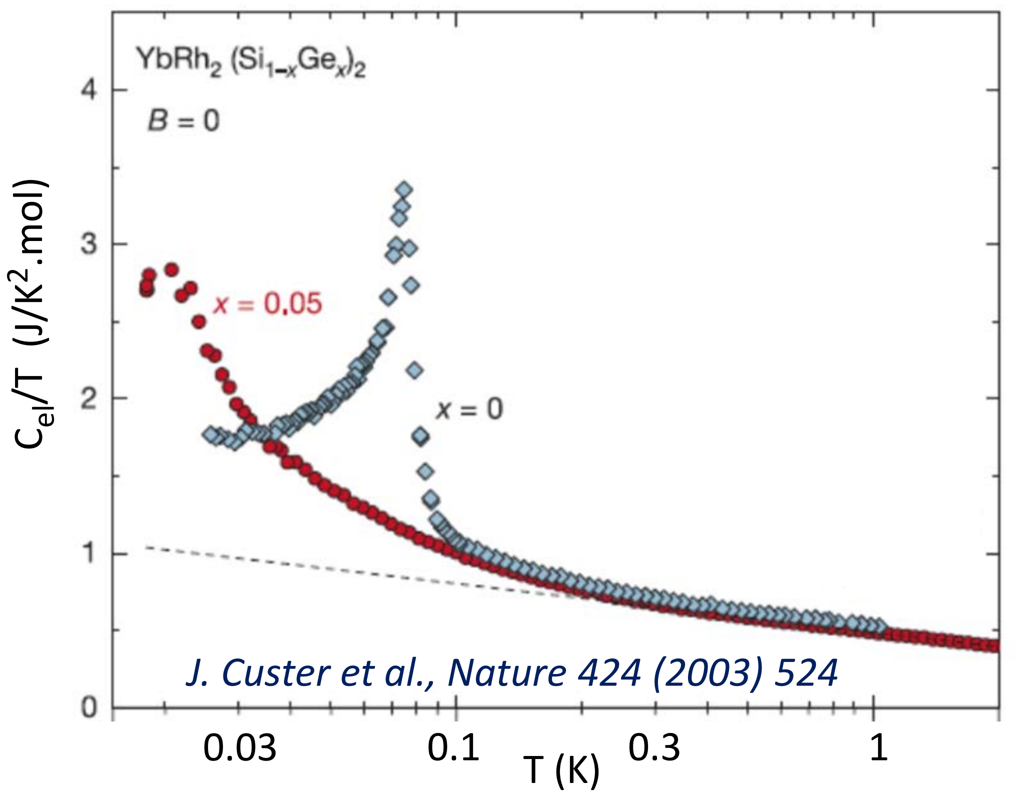
 - ΔC_{MF}: mean field step in C(T) at T_N
 - f depends on T dependence of C_{AFM}
 - $YbRh_2Si_2$: $C_{AFM}(T)/T \approx T^2$

 → $f \cong 0.1$

⇒ $\Delta G \approx 0.9$ mJ/(K.mol)

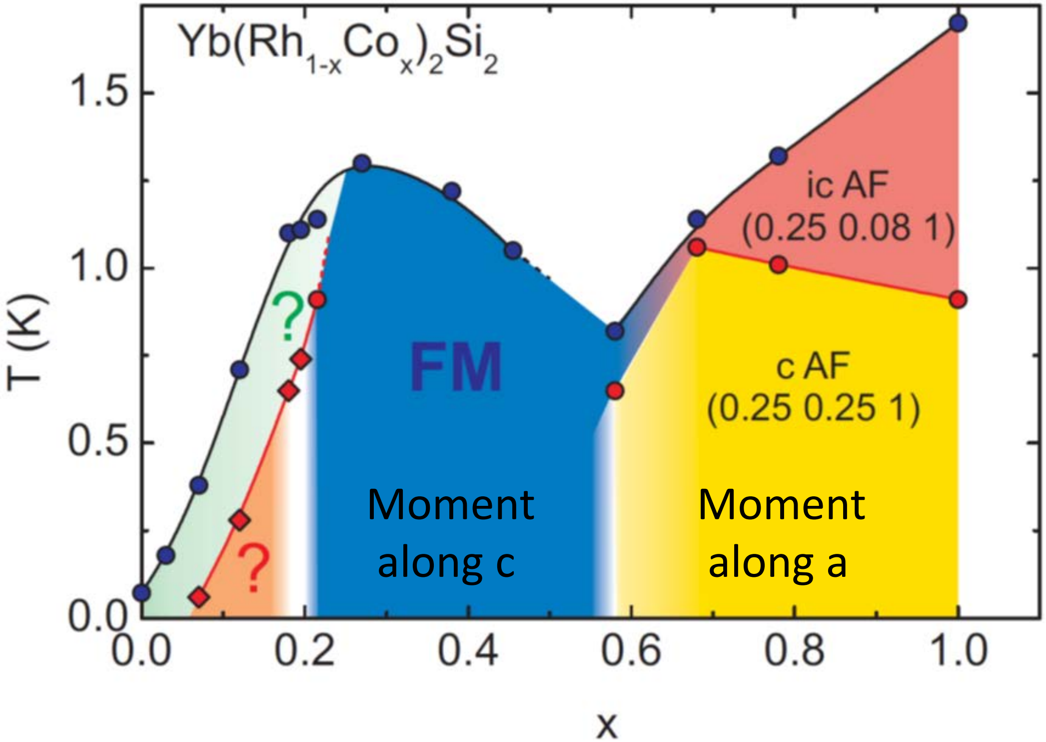
⇒ $\Delta G/R \approx 0.1$ mK

Specific heat of pure and 5 % Ge doped $YbRh_2Si_2$



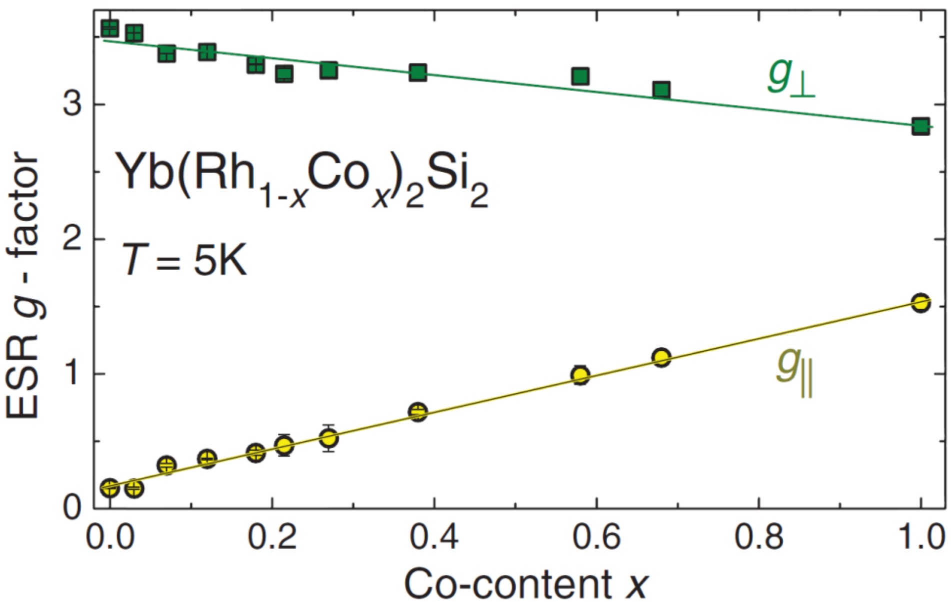
⇒ Kondensation energy of AFM state is of the order of 0.1 mK * k_B

Magnetic order in $YbRh_2Si_2$ - $YbCo_2Si_2$ system



- for x > 0.55: - AFM
  → ordered moment in basal plane
- for 0.22 < x < 0.58: - FM
  → Ordered moment along c direction
- for x < 0.27:
  - FM → canted AFM → AFM
  - some evidence that ordered moment has a component along c

Evolution of ESR g factors



- Switch between AFM and FM: no surprise
  → competition between AFM and FM exchange already known
- Switch in moment direction: mystery !
- ESR: → Easy plane character continuously increases with decreasing x

  ⇒ At x = 0.27 anisotropy a factor of 7!

Energy landscape of magnetic states in $YbRh_2Si_2$

- Small $\Delta E_{mag} \rightarrow$ (large moment) FM state close in Energy to (low moment) AFM state
- Consider hypothetical FM state with $m_{FM} = m_{sat}(B_c) = 0.10\ \mu_B$/Yb
- Calculation of differences in electr. free energy: standard approach used for superconductors

$\Rightarrow$ At B = 0, T = 0: $(G_{FM} - G_{AFM})/k_B = 2.3$ mK

$\Rightarrow$ FM state with "large" m_{4f} just 2.3 mK above AFM state with small m_{4f}

- Energy difference between AFM and PM state? = condensation energy of AFM state
- Can be estimated from specific heat data: $\rightarrow \Delta G = -\iint_0^{TN} (C_{AFM}(T) - C_{PM}(T))/T * dT^2$

$\Rightarrow$ At B = 0, T = 0: $(G_{PM} - G_{AFM})/k_B \approx 0.12$ mK

$\Rightarrow$ Kondensation energy of AFM state is of the order of 0.1 mK

Energy landscape of magnetic states in $YbRh_2Si_2$: very small energy scale

comparable to accessible gain in nuclear polarization energy