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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.998d - 2

Research Workshop on Condensed Matter Physics
30 June - 22 August 1997
MINIWORKSHOP ON
QUANTUM WELLS, DOTS, WIRES
AND SELF-ORGANIZING NANOSTRUCTURES
11 - 22 AUGUST 1997

"Rare-Earths in III-V Semiconductors Thin Films, Wires and Dots"

PART II

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Rare-Earths in III-V Semiconductors
Thin films, wires and dots
Part (II)

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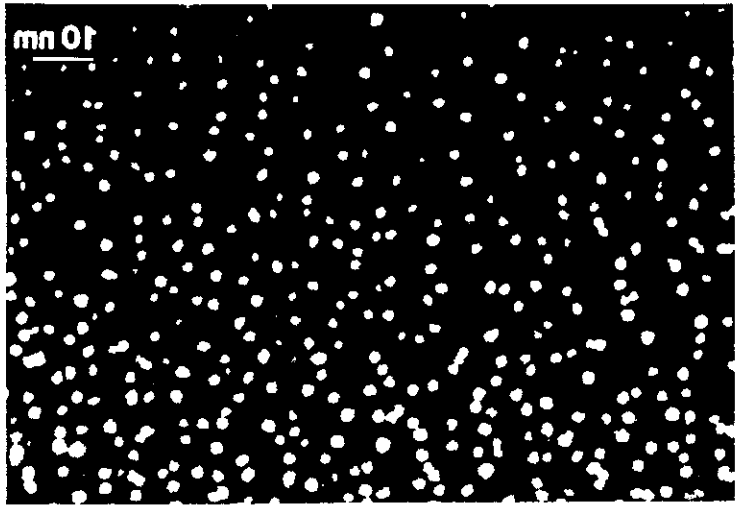
Overview

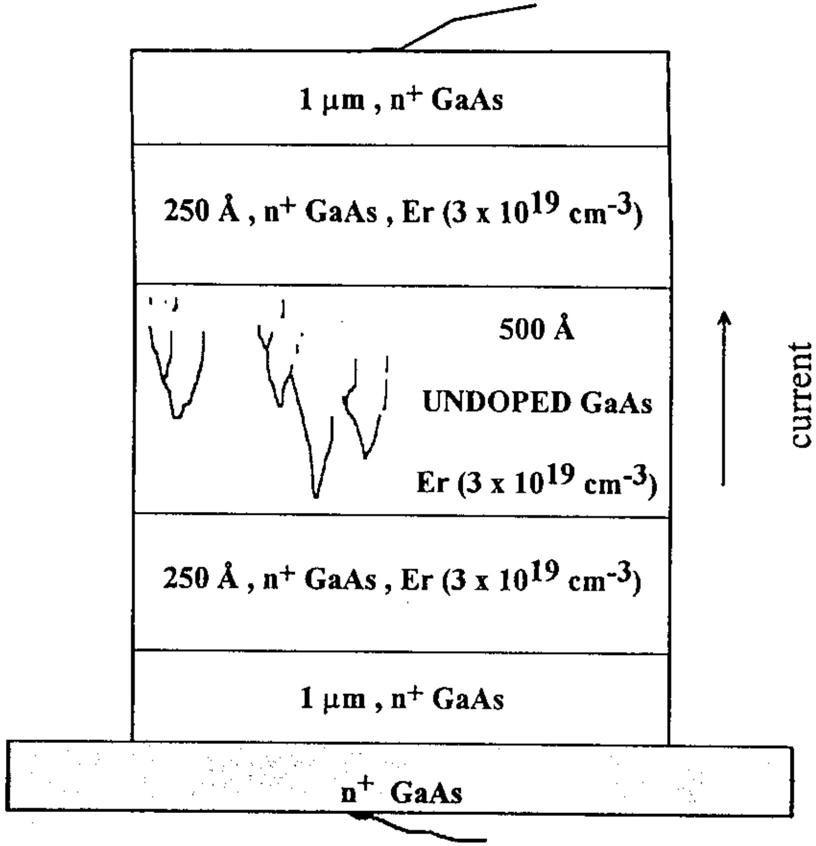
- Sample description
- Transport
  - -Universal Conductance Fluctuations
  - -Telegraph Noise Spectroscopy
- Magnetic Properties of ErAs
  - -Magnetic moment of an ErAs cluster
  - -Thermally activated switching
- Rotation
  - -Probing the magnetic anisotropy
- Macroscopic Quantum Tunnelling (MQT)
  - -Tunnelling of the magnetisation

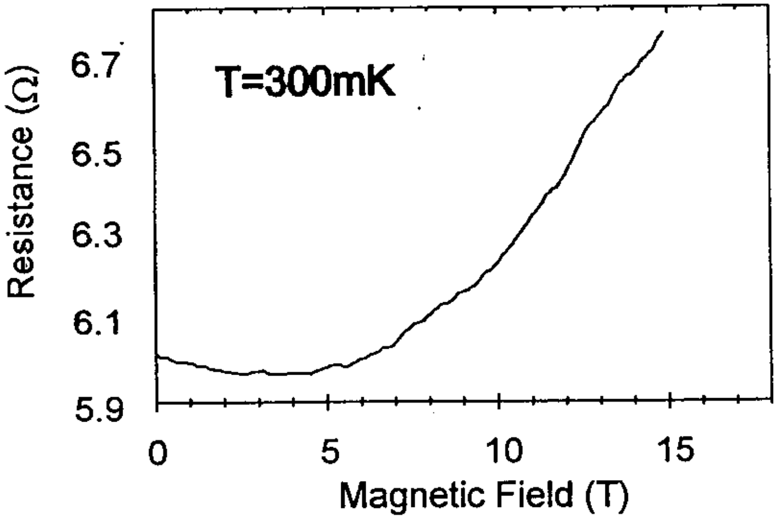
UMIST

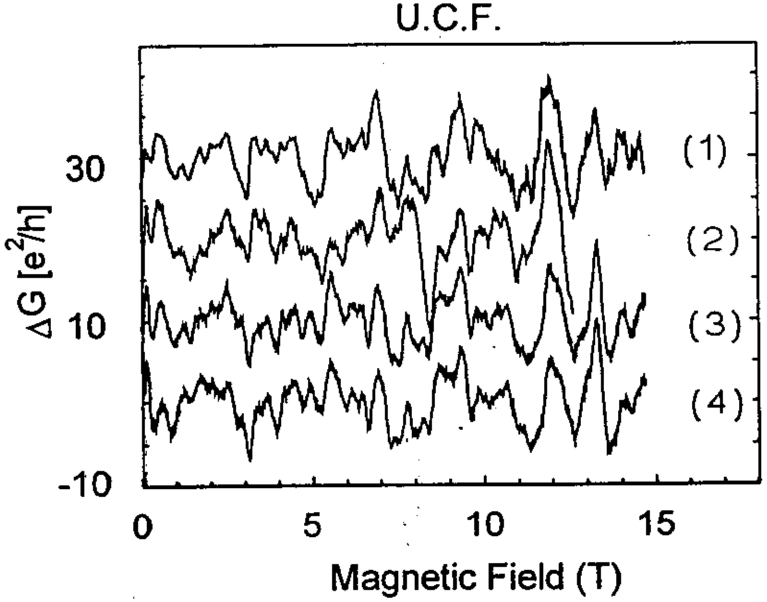
QUANTUM DOTS



After Poole et al. J. Cryst. Growth 121, 121 (1992)

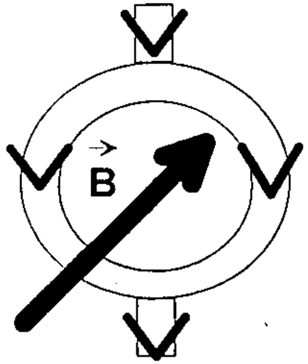






Universal Conductance Fluctuations

* AHARONOV-BOHM EFFECT

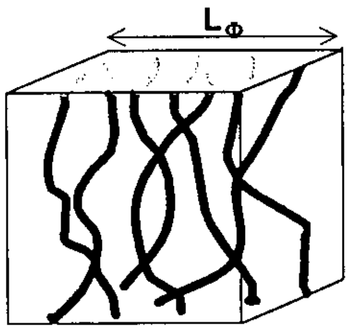


$$\Delta\varphi = \frac{2\pi\Phi}{\Phi_o}$$

$$\Phi = \vec{B}.\vec{S}$$

$$\Phi_o = \frac{h}{e}$$

* PHASE COHERENT SYSTEM



G will Change by $\frac{e^2}{h}$ if

- B is changed by $B_c = \frac{\Phi_o}{L_\Phi^2}$

- E_f is changed by $E = \frac{\hbar D}{L_\Phi^2}$

- An impurity is moved

➔ Magnetic Correlation Length : $B_c = 0.15$ T

➔ Typical Surface for the Interference : $S_i = 0.03\ \mu m^2$

➔ Circle With a Diameter of $L_\Phi = 100$ nm

➔ Surface of the Mesa : $S = 34000\ \mu m^2$

➔ Number of Sub-System in Parallel : $\frac{34000}{0.03} = 3.10^6$

➔ Expected Amplitude of the Fluctuations : $1000\frac{e^2}{h}$

➔ Experimental Amplitude of the Fluctuations : $3\frac{e^2}{h}$

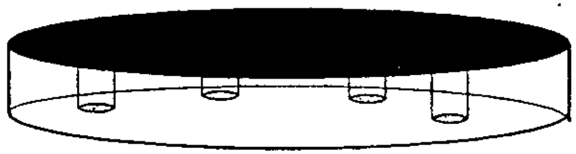
Hypothesis

Transport is dominated by only few sub-systems in parallel

CONCLUSION

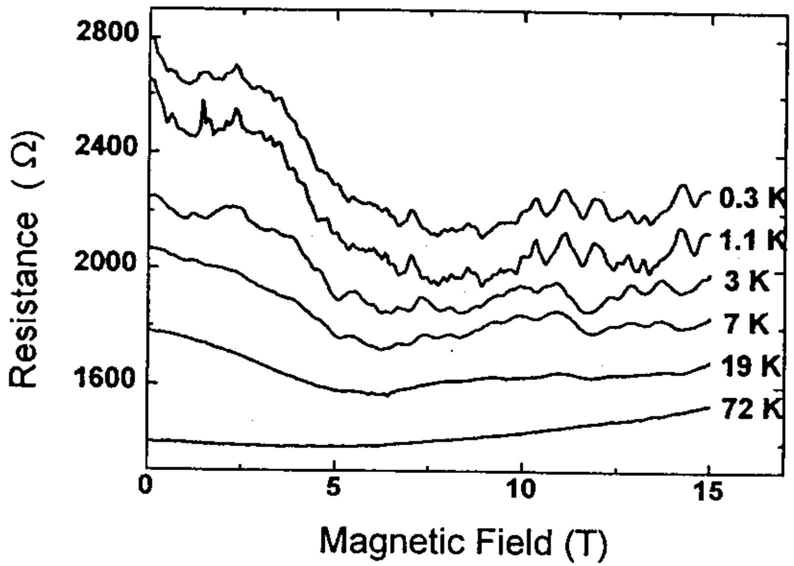
➔ PHASE COHERENT PHENOMENA

➔ FEW SUB-SYSTEMS IN PARALLEL

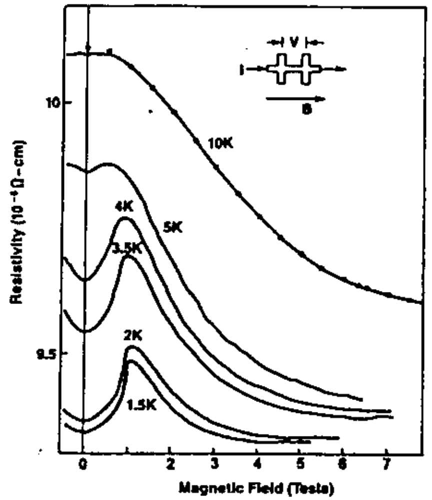


➔ IMPORTANT FOR THE OBSERVATION OF A A "CHANGE OF STATE" IN THE SAMPLE.

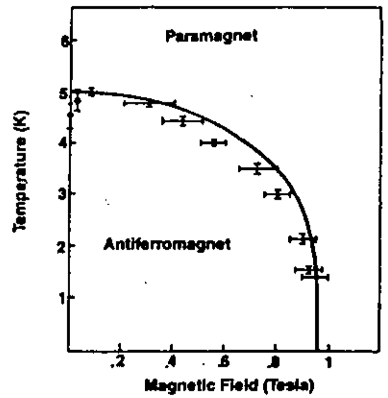
TEMPERATURE DEPENDENCE



Magnetic Properties of ErAs

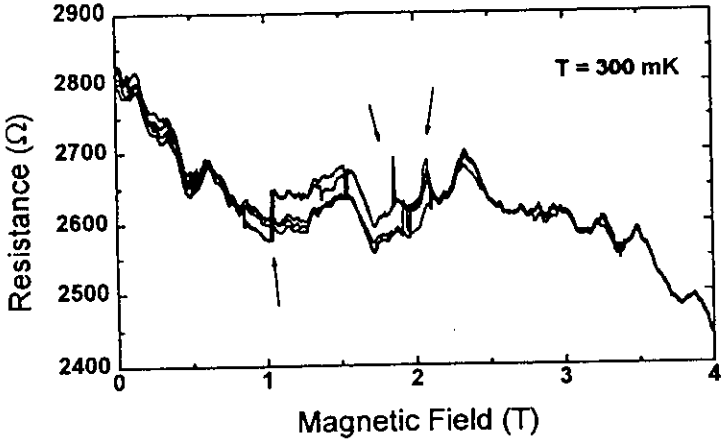


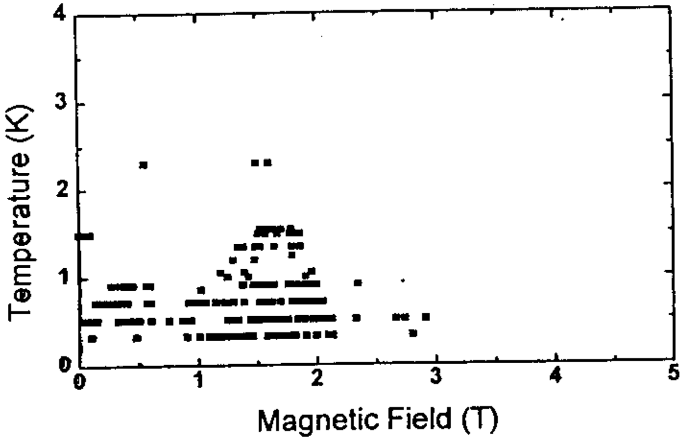
Longitudinal magnetoresistance as a function of temperature for a thin (3 monolayer) ErAs sample. Taken from Allen et. al.PRL **62**, 2039 (1989)

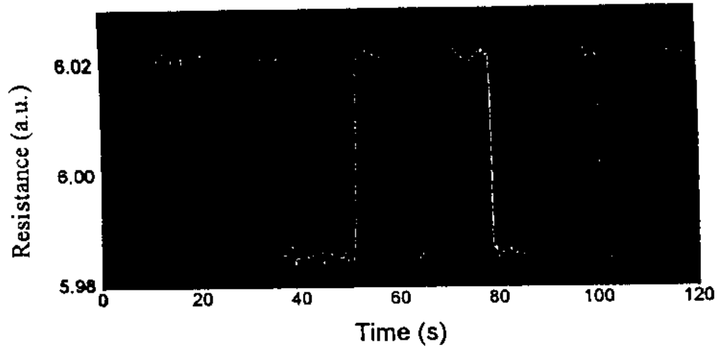


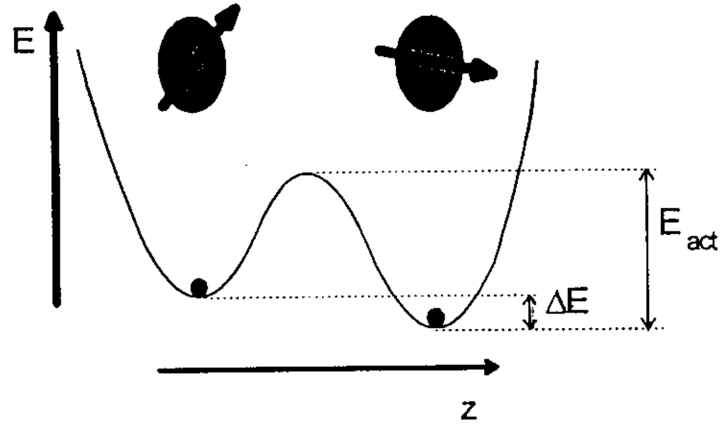
Low temperature magnetic phase diagram of ErAs. Taken from Allen et. al. PRL. **62**, 2039 (1989)

INSTABILITIES





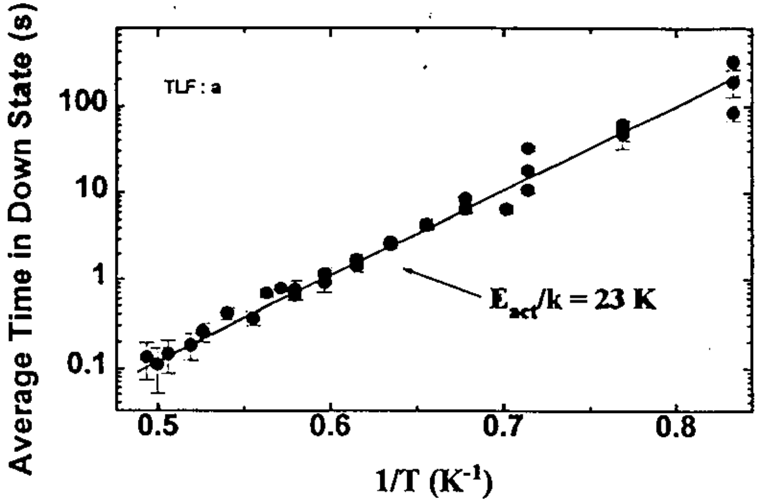


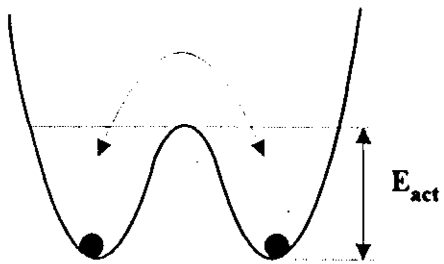


$$< \tau_u >= \tau_{o,u} \exp \frac{E_{act,u}}{kT}$$

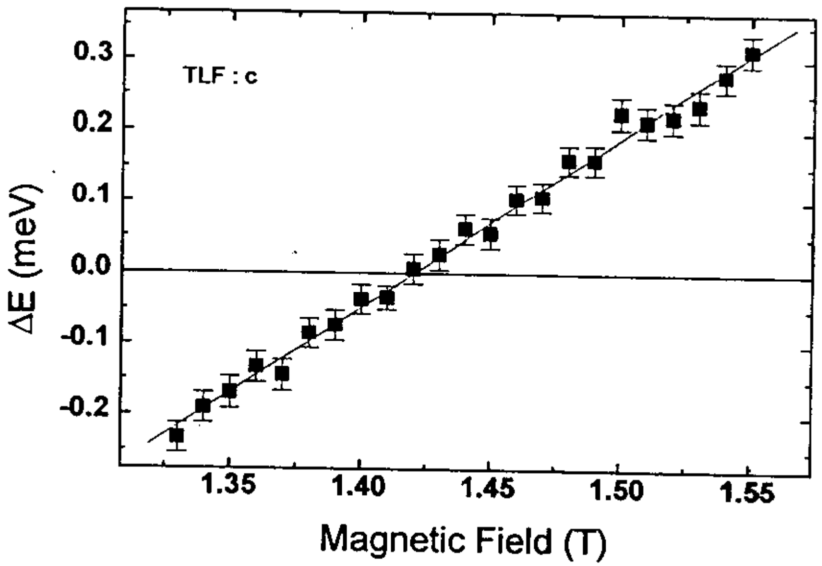
$$< \tau_d >= \tau_{o,d} \exp \frac{E_{act,d}}{kT}$$

$$\Delta E = kT \ln\left(\frac{< \tau_u >}{< \tau_d >}\right)$$

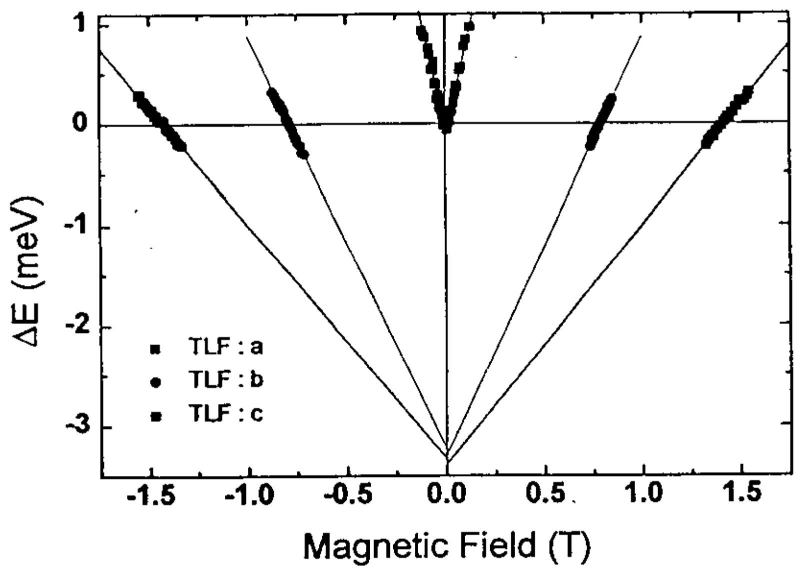


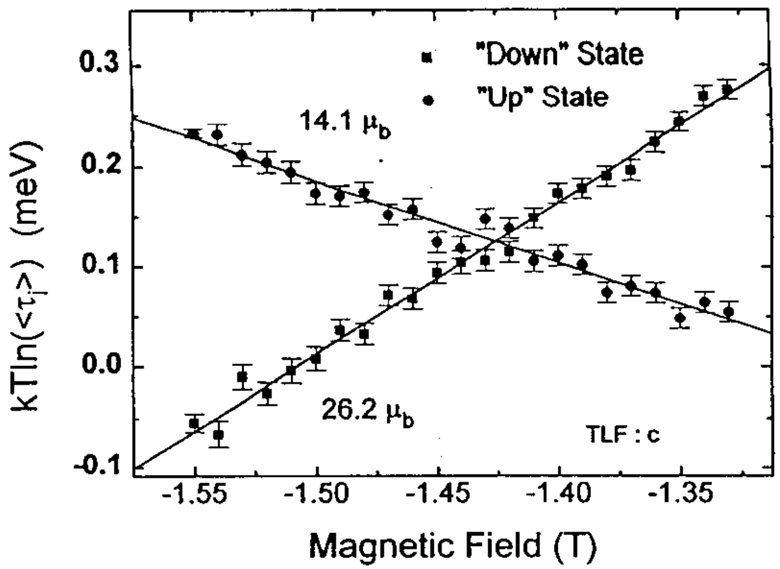


$$\langle\tau_d\rangle = \tau_{o,d} \exp\frac{E_{act,d}}{kT}$$



$$\Delta E = E(0) + \Delta\vec{m}\cdot\vec{H}$$

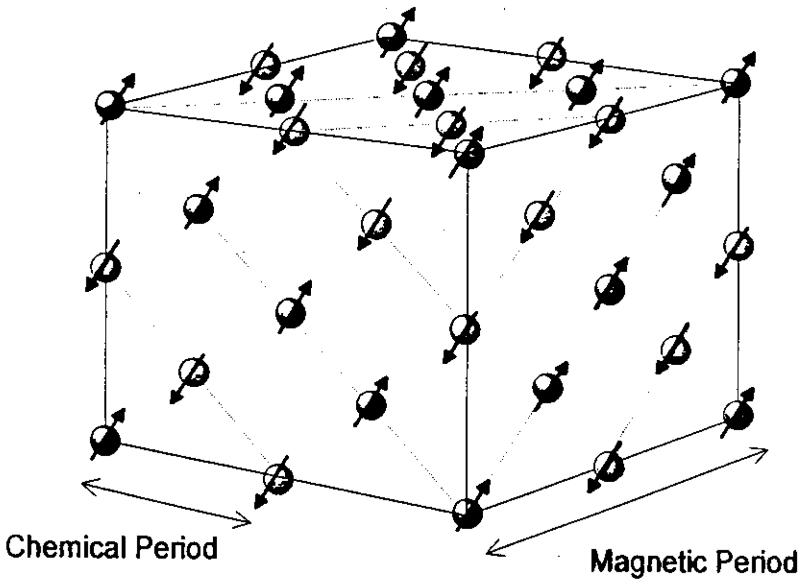




	H<0		H>0	
TLF	m_u-m_b	m_d-m_b	m_u-m_b	m_d-m_b
a	104 ± 9	-50 ± 8	113 ± 5	-47 ± 9
b	-30 ± 0.6	41 ± 0.7	-29 ± 1	44 ± 1.1
c	26 ± 0.6	-14 ± 0.5	27 ± 0.6	-14 ± 0.6

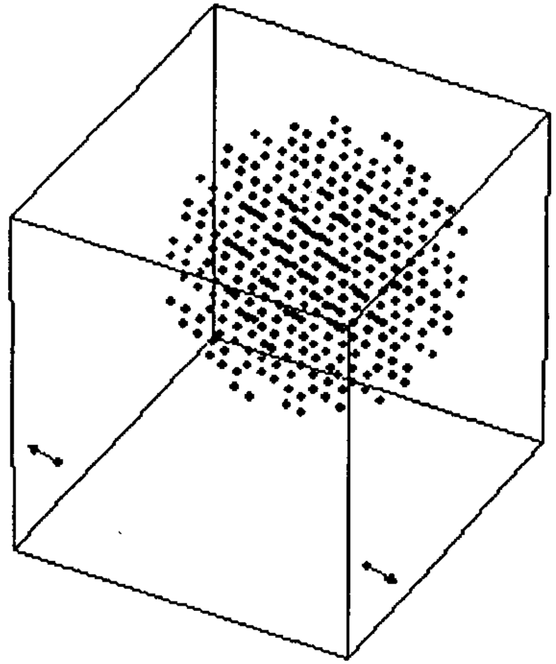
(in units of μ_b)

ErAs



(Redrawn from Kittel)

- 6 easy axes in a (111) plane
- 5.3 μ_b / Erbium atom



Number of Erbium atom in the cluster ~ **1000**

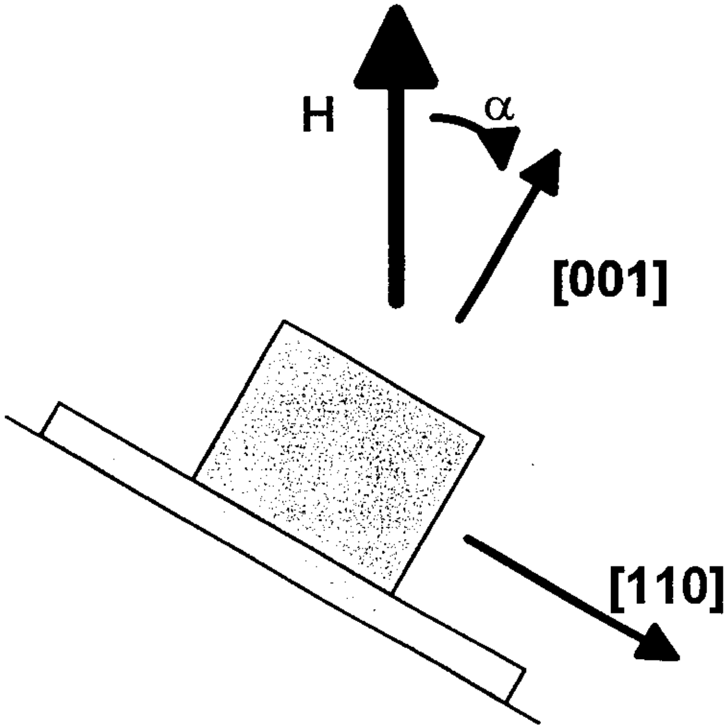
Number of atom at the surface ~ **100**

Number of atom at the surface with a non compensated magnetic moment ~ **10**

Total magnetisation of the cluster :

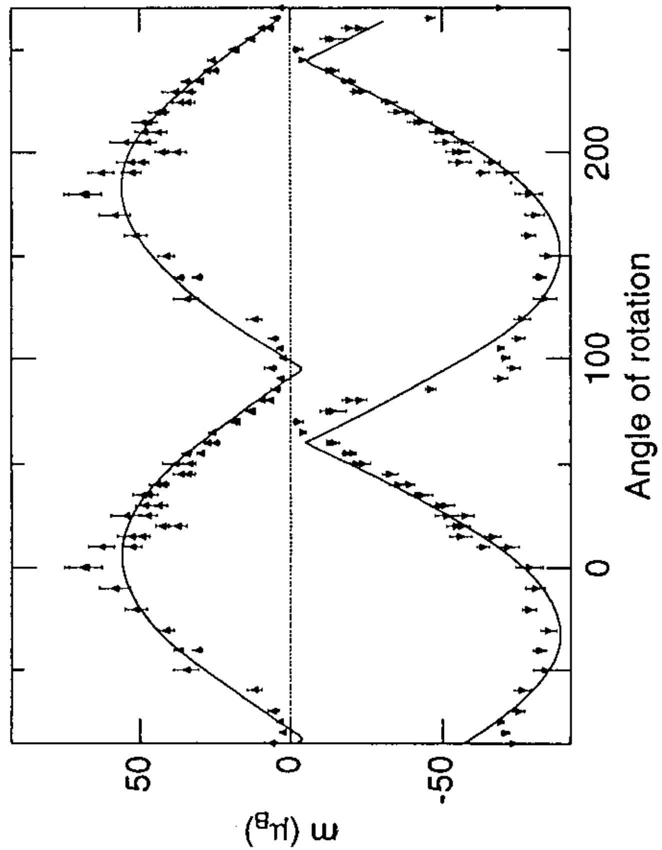
$$\sim \mathbf{10 \times 5.3 \sim 50}\ \mu_b$$

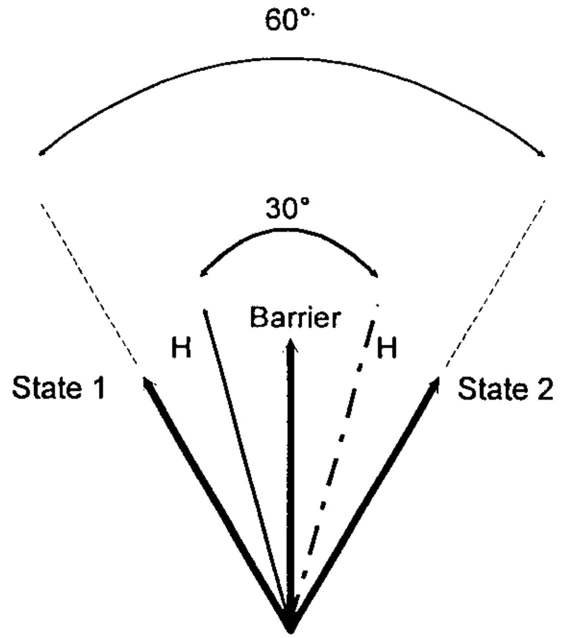
ROTATION



- *in situ*

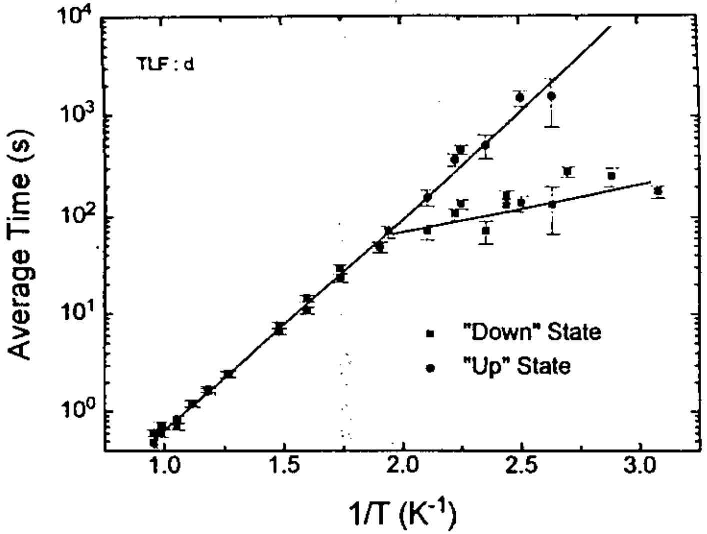
Angular dependence

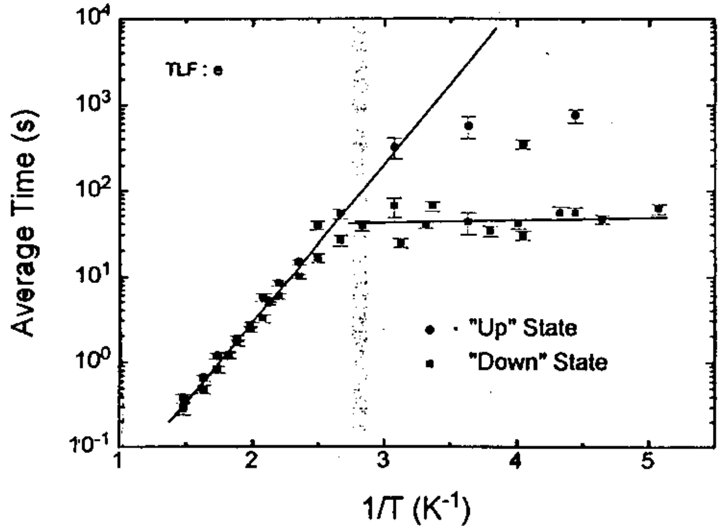


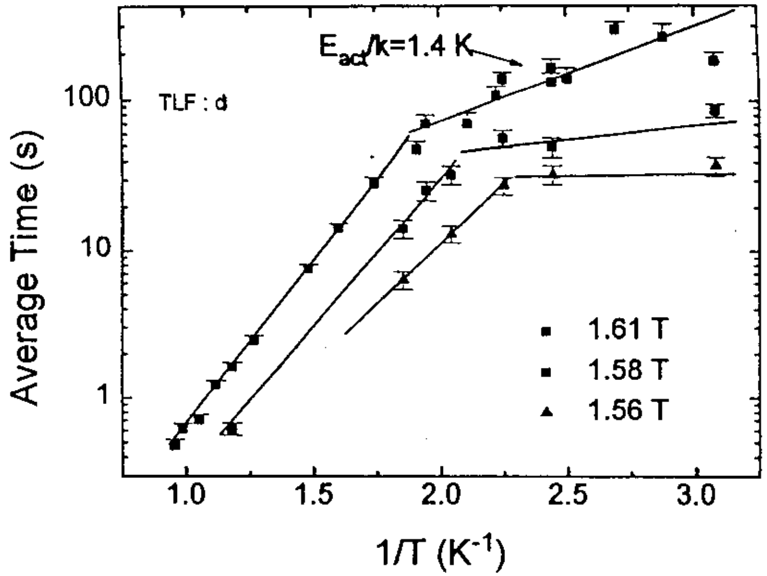


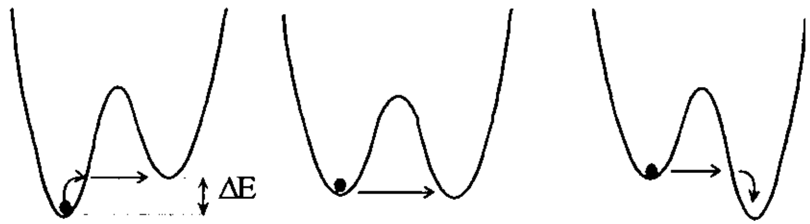
60°
30°
Barrier
H
H
State 1
State 2

Macroscopic Quantum Tunnelling (MQT)









$E_{act,d} > E_{act,u}$

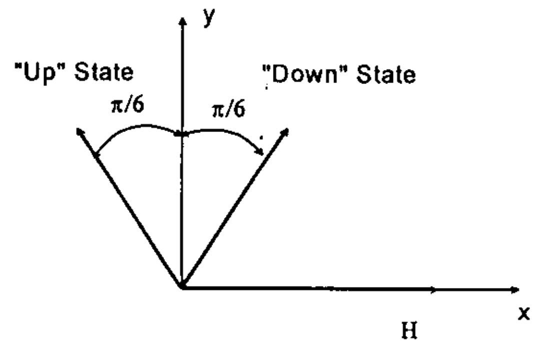
Thermally Activated tunnelling

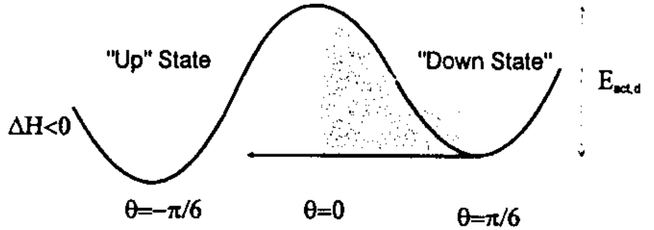
$E_{act,d} = E_{act,u}$

Tunnelling

$E_{act,d} < E_{act,u}$

Tunnelling

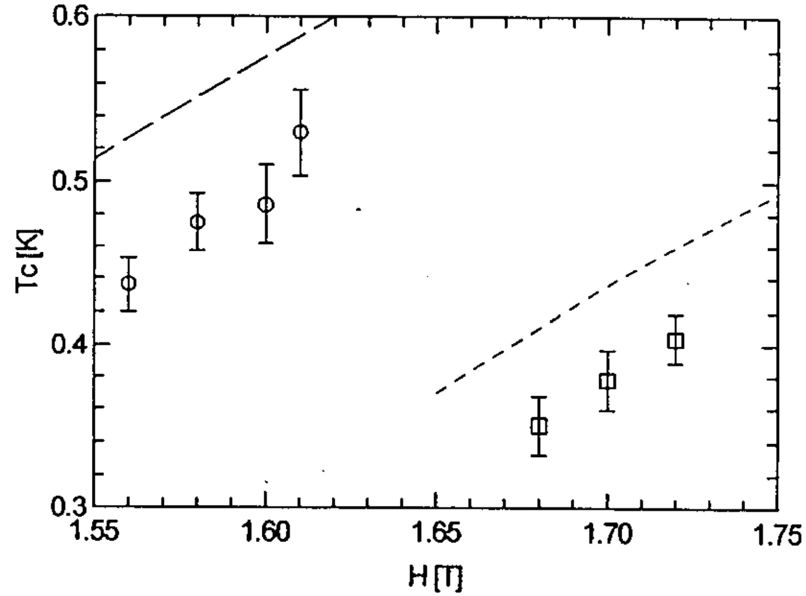




$$B_{WKB} \propto \int_0^{\pi/6} \sqrt{E(\theta) - E(\pi/6)}\, d\theta \;\rightarrow\; B_{WKB} = B_0 \sqrt{1 + \frac{M_d(H - H_0)}{E_0}}$$

$$E_{act,d} = E_0 + M_d(H - H_0)$$

$$T^* = \frac{E_0}{kB_0}\left(1 + \frac{M_d(H - H_0)}{2E_0}\right)$$



Equating the thermal and tunnel rates :

$$e^{\frac{-(E_o + M_d(H - H_o))}{KT_c}} = e^{-\beta_o \sqrt{(1 + \frac{Md(H - H_o)}{E_o})}}$$

$$\Rightarrow \quad T_c(\Delta H) = \frac{E_o}{K\beta_o}\sqrt{1 + \frac{M_B \Delta H}{E_o}}$$

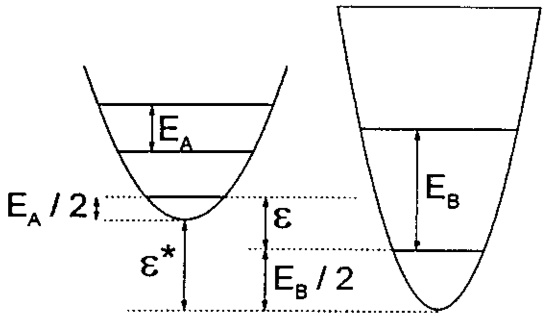
where $\Delta H = H - H_o$ and $\beta_o = \ln[\tau(H_o)/\tau_o]$ can be estimated from the tunnelling rate when the two states are aligned.

Detailed Balance

- Detailed balance i.e. the dwell time in a state is proportional to the probability of being in that state, is UNIVERSAL and MUST be obeyed in all systems.

- For a two level system : $\frac{\langle\tau_1\rangle}{\langle\tau_2\rangle}=\frac{P_1}{P_2}=\exp\left(\frac{\varepsilon}{kT}\right)$

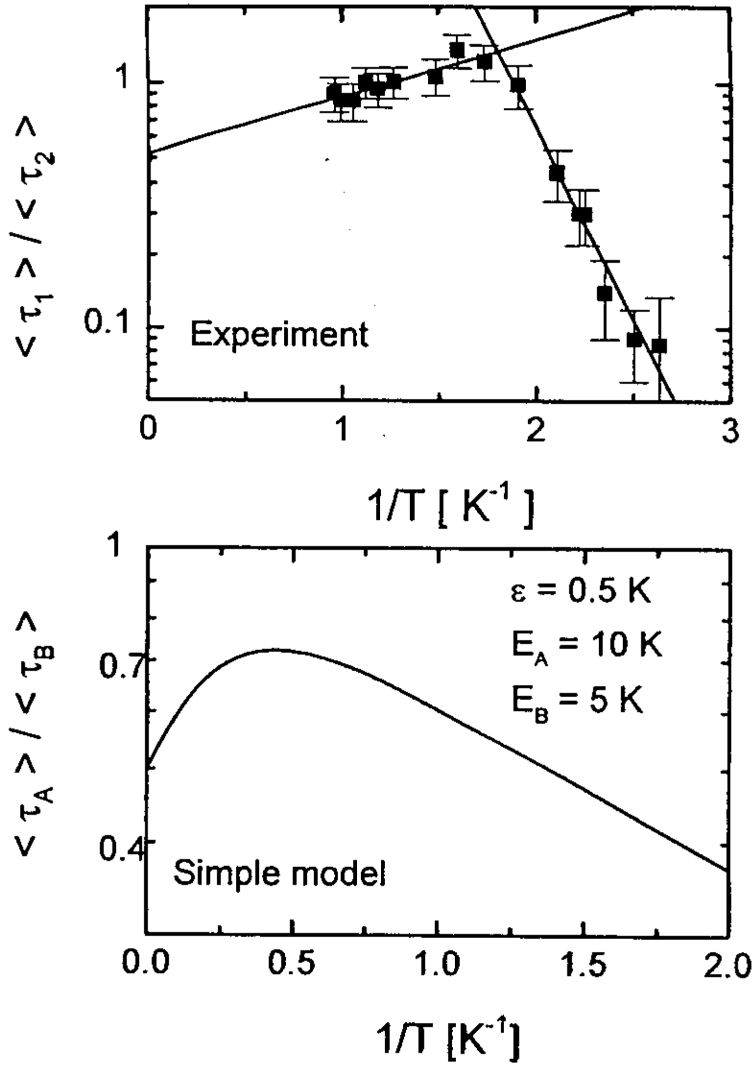
- Apparent deviation from detailed balance in our system can be explained by considering excited magnetic states.



Assume parabolic potential for wells A and B :

$$\frac{P_A}{P_B}=\frac{\sum_{n=0}^{\infty}\exp\left[-\left(\frac{\varepsilon^*+(n+\frac{1}{2})E_A}{kT}\right)\right]}{\sum_{n=0}^{\infty}\exp\left[-\left(\frac{(n+\frac{1}{2})E_B}{kT}\right)\right]}=\frac{\sinh\left(\frac{E_B}{2kT}\right)}{\sinh\left(\frac{E_A}{2kT}\right)}\exp\left(\frac{-\varepsilon^*}{kT}\right)$$

$$\frac{P_A}{P_B}\approx\frac{E_B}{E_A}\exp\left(\frac{-\varepsilon^*}{kT}\right)$$ if both E_A and E_B << kT



Conclusion

- Self organised ErAs quantum dots and wires can grown by MBE.
- Transport is phase coherent and sensitive to the spin orientation of a particular ErAs cluster.
- Simply measuring the resistance it is possible to monitor the orientation of the cluster in real time.
- Telegraph noise spectroscopy allows to determine the magnetic moment carried by the ErAs cluster.
- This technique can measure magnetic moments as small as $\sim 10\mu_B$ and is therefore 5-orders of magnitude more sensitive than DC-SQUID techniques.
- At high temperature the switching is thermally activated.
- At low temperature it is tunnelling which dominates.
- The tunnelling is referred to as Macroscopic Quantum Tunnelling (MQT) as it is a macroscopic object (the giant spin of the cluster) which tunnels.
- Detailed balance allows us to conclude that excited magnetic states are important for our system.