NMR Studies of the Iron Based Superconductors

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Cade o UC Davis?



Universidade da California

10 campuses 238700 Undergraduates 50400 Postgraduate 19700 Academic Staff

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Outline

•The Iron Superconductors

•Nuclear Magnetic Resonance

•Glassy Dynamics and Inhomogeneity

•Nematicity and Disorder

Superconductor families

hydrogen																		heilum
1																		2
H																		He
1.0079																		4.0026
Ithium	beryflium												boron	carbon	nitrogen	cxygen	fluorine	noon
3	_4												5	6	7	8	9	10
Li	Be												в	C	N	0	F	Ne
6,941	9.0122												10.811	12.011	14.007	15.999	18.998	20,180
sodium	magnesium												aluminium		phosphorus	40	chilorine	argon
1.1	12												13	14	15	10		18
Na	Mg												AI	SI	Р	S	CI	Ar
22.990	24.305							_					26.982	28.095	30.074	32.065	35.453	39.948
potassium	caldium 20		scandium	stanium 22	vanadium	chromium 24	manganese 26	100	cobalt 27	nickel	copper	zine 20	gallum	germanium	arsenic 22	selenium 24	tromine 25	krypton 26
19	20		<i>.</i>	. .	23	24	25	20	<i>"</i>	20	20	- 30	~	34	33	34	35	30
K	Ca		SC		V	Cr	Mn	ьe	Co	NI	Cu	Zn	Ga	Ge	As	Se	Br	Kr
39.098	40.078		44.956	47.867	50.942	51.996	54.938	55.845	58.933	58.693	63,546	65.39	69.723	72.61	74.922	78.96	79.904	83.80
rubidium 27	strontium 20		yttrium 20	zirconium 40	nicblum	molybdenum 42	technetium	44	rhodium	palladium AC	47	cadmium 49	indium 40	tin 60	E1	tellurium 62	iodine 62	xenon E4
DI	ő		Ň		NIL.		-	D	DI	DI		0.1		n in its in the second	O.	-		N.
RD	Sr		I Y	Zr	ND	IVIO	IC	ĸu	Rn	Pa	Ag	Ca	In	Sn	5 D	Ie		хе
85.468	87.62		88.906	91.224	92.906	95.94	[98]	101.07	102.91	106.42	107,87	112.41	114.82	118.71	121.76	127.60	126.90	131.29
55	56	57-70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	astatine 85	86
Ca	Do	×	1	LIE	To	14/	Do	00	1m	D4	۸	Lla	TI	Dh	Di	Do	A 4	Dm
US	Da	*	Lu		Ia	vv	ĸe	US		Pι	Au	пg		PD	ы	PO	Aι	RU
132.91 franckum	137.33 radium		174.97 Investigation	178.49 outbodientium	180.95 @colum	183.84 seaboratum	186.21 hobdum	190.23 bassium	192.22 moltradum	195.08 ucunolitum	196.97 UPU(00000	200.59 UDUITEUM	204.38	207.2	208.98	209	[210]	[222]
87	88	89-102	103	104	105	106	107	108	109	110	111	112		114				
Er	Da	XX	1 m	Df	Dh	Sa	Ph	He	N/14	Hum	11	Hub		Llug				
	na	~ ^		INI	DD	Jy	DII	115	IALC	oun	ouu	oub		ouq				
223	[226]		[262]	[261]	[262]	[266]	[264]	269	268	[271]	[272]	277		289				

*Lanthanide series	lanthanum 57	58	praseodymium 59	neodymium 60	promethium 61	62	europium 63	gadolinium 64	65	dysprosium 66	holmium 67	ertium 68	69	ytterbium 70
	La 138.91	140.12	Pr 140.91	Nd	Pm	Sm	EU 151.96	Gd	158.93	Dy 102.50	HO 164.93	Er 167.26	168.93	173.04
**Actinide series	actinium 89	90	protactinium 91	uranium 92	neptunium 93	plutonium 94	americium 95	curium 96	berkelium 97	calfornium 98	einsteinium 99	fermium 100	nendelevium 101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
	[227]	232.04	231.04	238.03	[237]	[244]	[243]	[247]	[247]	[251]	[252]	[267]	[258]	[259]

Unconventional superconductor families:

Heavy fermions	T _c ~ 2 K	1979
Organics	Т _с ~ 10 К	1990
Cuprates	T _c ~ 100 K	1987
Iron Arsenides	Т _с ~ 40 К	2008

Superconductor families

Conventional:

- Well described by BCS theory
- Cooper pairing driven by phonons
- Typically elements or simple compounds
- (Al, Hg, MgB₂, Nb₃Sn, Nb-Ti alloy...)
- Zero spin and angular momentum

Unconventional:

- •Unknown pairing mechanism (spin fluctuations?)
- Finite spin or angular momentum
- Often found in close to (anti)ferromagnetism

The Iron Arsenide Family

Condens. Matter Phys. (2010)

Tokyo Inst. Tech.

Superconductivity and Magnetism

Antiferromagnetic metal

Zero resistance

But the details are very different!

Orthorhombic Distortion

(a-b)/a ~ 1%

Magnetic Order

Stripe ordering:

 $Q_{AF} = (\pi/a, 0, \pi/c)$

Moments point along (100)

First order for pure compound

Material	Ordered Moment
CaFe ₂ As ₂	$0.80 \ \mu_{\text{B}}$
BaFe ₂ As ₂	$0.87~\mu_{B}$
SrFe ₂ As ₂	1.01 μ_B
LaFeAsO	$0.4 \ \mu_{\text{B}}$

Goldman et al, PRB 79 24593 (2008)

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As NMR

Canfield and Bud'ko, Annu. Rev. Condens. Matter Phys. (2010)

As Hyperfine Coupling

Temperature (K)

Nuclear Spin Dynamics

$$|I_{7}=+\frac{1}{2}>$$

$$I_z = -\frac{1}{2}$$

By applying rf pulses, we can perturb the equilibrium Boltzmann distribution, and then watch as the system relaxes to a finite spin temperature

$$M(t) \sim 1 - e^{-t/T_1}$$

$$(T_1T)^{-1} \sim \lim_{\omega \to 0} \frac{\chi''(\mathbf{q},\omega)}{\omega}$$

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Spin Lattice Relaxation

Divergence reveals critical slowing down of magnetic fluctuations at AFM phase transition

Critical Slowing Down High temperature, random fluctuations Near transition, slow correlated fluctuations

Low temperature, long-range order

Under the Rug: A Closer Look

Not all the nuclei see the same fluctuations!

Dynamical Heterogeneity

$$M(t) = \int \mathcal{P}(W_1) f(W_1 t) dW_1$$

Distribution of $1 - e^{-W_1 t}$

 $\mathcal{P}(W_1)$ characterized by two parameters (fit to log-normal distribution):

$$T_1^{-1}$$
 and σ_1

Ba(Fe_{0.938}Co_{0.062})₂As₂, H₀ = 11.7 T

Temperature Dependence

Standard deviation σ_1 increases by 2 orders of magnitude below 100 K

Signal Wipeout

Glassy Behavior

•General feature in statistical mechanics when ergodicity is broken (structural glasses, polymers, spin glasses, etc.)

•symmetry breaking in systems with *disorder*

Dynamical Heterogeneity

Parisi and Sciortino, Nat. Mat. 2013

Doping Dependence

Dynamical inhomogeneity develops below 100 K, and is more pronounced near the critical doping x = 0.07

•Glassy behavior also has been reported via NMR in: LaFeAs(O,F) (Hammerath PRB 2013) , Ba(Fe,Rh)₂As₂ (Bossoni, PRB 2013), and Ba(Fe,Cu)₂As₂ (Imai, PRL 2014)

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Nematic Order

Nematic Susceptibility

Chu et al., Science 2012

Apply strain ε_p , measure nematicity $\eta = \Delta \rho / \rho_0$

nematic fluctuations in paramagnetic state

Nematic Fluctuations Drive Spin Fluctuations

Fernandes et al., PRL 2013

Magnetoelastic coupling leads to scaling between shear modulus and NMR T_1T

Effect of Disorder

•Nematic order has Ising symmetry

•Dopants/disorder introduce local field gradients -> act as random field

•Random fields in Ising model (Imry & Ma PRL 1975):

- •Suppression of long range nematic order
- •Inhomogeneous glassy dynamics

Carlson and Dahmen, Nat. Comm. 2010 Carlson et al., PRL 2006 Mezard & Monnason, PRB 1994

Random Field Ising Model

$$H = -J\sum_{\langle i,j \rangle} \sigma_i \sigma_j - \sum_i (h+h_i)\sigma_i$$

randomly distributed field from local disorder/dopants

(a)Color visualization

(b)Stripe visualization

Kivelson et al., PRL 2006; Loh, Carlson and Dahmen, PRB 2010

Temperature Dependence

Loh, Carlson and Dahmen, PRB 2010

•NMR reveals dynamical inhomogeneity

•Glassy dynamics persists up to 100 K in a broad range of materials (Ni, Co, Cu, Rh, P doped BaFe₂As₂, LaFeAsO_{1-x}F_x)

•Frozen AF clusters coexist with SC

•Likely origin is *disorder in the vicinity of the nematic quantum critical point*