NEUTRONS AND THEIR INTERACTION WITH MATTER

NEUTRONS AND THEIR INTERACTION WITH MATTER

Overview

- **History – neutrons and nuclear reactions**

- **Production – reactors and spallation sources**

- **Properties – as a particle and a probe**

- Instruments – exploiting the probe to do science

NEUTRONS
FOR SOCIETY

A BIT OF HISTORY

The neutron

- 1932: J. Chadwick, after work by others, discovers the 'neutron', a neutral but massive particle

$$^{4}_{2}\text{He} + ^{9}_{4}\text{Be} \rightarrow ^{12}_{6}\text{C} + ^{1}_{0}\text{n}$$

$$\left(m_{\text{He}} + m_{\text{B}}\right)c^{2} + T_{\text{He}} = \left(m_{\text{C}} + m_{\text{n}}\right)c^{2} + T_{\text{C}} + T_{\text{n}}$$

$$m_{\text{n}} = 1.0067 \pm 0.0012 \, \text{a.m.u}$$

To pump

Polonium
(source of alpha particles)

To amplifier and oscilloscope

Neutron chamber   Beryllium   Paraffin wax target   Ionization chamber

NEUTRONS FOR SOCIETY

A BIT OF HISTORY

The nuclear reaction

- 1938: O. Hahn, F. Strassmann & L. Meitner discovered the fission of ^{235}U nuclei through thermal neutron capture

- 1939: H. v. Halban, F. Joliot & L. Kowarski showed that ^{235}U nuclei fission produced 2.4 n^0 on average – chain reaction

- 1942: E. Fermi & al. demonstrated first self-sustained chain reaction reactor

Chicago pile:
360T of graphite
50T of U and UO
0.5W power

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NOBEL PRIZES, NEUTRONS AND THE ILL

Chadwick, Shull & Brockhouse

The Nobel Prize in Physics 1994

The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.

James Chadwick (1891 - 1974)

Clifford G. Shull, MIT, Camebridge, Massachusetts, USA, receives one half of the 1994 Nobel Prize in Physics for development of the neutron diffraction technique.

Shull made use of **elastic scattering** i.e. of neutrons which change direction without

Betram N. Brockhouse, McMater University, Hamilton, Ontario, Canada, receives one half of the 1994 Nobel Prize in Physics for the development of neutron spectroscopy.

Brockhouse made use of **inelastic scattering** i.e. of neutrons, which change

NEUTRONS FOR SOCIETY

Nobel prizes, neutrons and the ILL

Haldane (1977 – 1981), Kosterlitz and Thouless for topological phase transitions and phases of matter (Electronic structure and excitation of 1D quantum liquids and spin chains)

NEUTRON SOURCES

Fission reactors

- Nuclear fission → chain reaction with excess neutrons (1n → 2.5n)

- Slow neutrons split U-235 nuclei

- Fission neutrons have MeV energies and need to be moderated (thermalized) to meV energies by scattering from water

- Thermalisation @ RT → *thermal* neutrons, @ 25K → *cold* neutrons and @ 2400 K → *hot* neutrons

- ILL – flux 1.5 x 10^{15} n/cm^2/s

Fission
Uranium 235
slow neutron   fission of the excited nucleus   chain reaction triggered by moderated neutrons

Neutron sources

Spallation sources

- Neutrons can be produced by bombarding heavy metal targets
- 2 GeV protons (90% speed-of-light) produce spallation – evaporation of ~30 neutrons

Neutron sources

(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Continuous or pulsed beams

Integrated vs peak flux – ESS will have a time-integrated flux comparable to ILL

CONTINUOUS OR PULSED BEAMS

Integrated vs peak flux – ESS will have a time-integrated flux comparable to ILL

adapted version of IAEA-TECDOC

N vs X

ESRF (hard X-rays)

NEUTRONS
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The neutron

As a particle

free neutrons are unstable: β-decay → proton, electron, anti-neutrino

life time: 888 ± 1 sec *or* 880 ± 1 sec !!!!!

wave-particle duality: neutrons have particle-like and wave-like properties
- mass: m_n = 1.675 x 10^{-27} kg = 1.00866 amu. (unified atomic mass unit)
- charge = 0
- spin =1/2
- magnetic dipole moment: μ_n = -1.9 μ_N, μ_p = 2.8 μ_N, μ_e ~ 10^3 μ_n,
- velocity (v), kinetic energy (E), temperature (T), wavevector (k), wavelength (λ)

NEUTRONS
FOR SOCIETY

THE NEUTRON

As a particle

- Velocity (v), kinetic energy (E), temperature (T), wavevector (k), wavelength (λ)

$$E = m_n v^2 / 2 = k_B T = (hk/2\pi)^2 / 2m_n = (h/\lambda)^2 / 2m_n$$

- Neutron energy determines velocity and therefore time-of-flight (*tof*) over a given distance i.e. *tof* → energy determination

$$tof = \frac{L}{v} = 253\,\mu\sec\cdot\lambda\left[\overset{o}{A}\right]\cdot L[m]$$

THE NEUTRON

As a probe

	Energy	Temperature (K)	Wavelength (nm)	velocity (m/s)
Ultra cold neutrons	< 10 μeV	< 0.05	> 30	< 15
Cold neutrons	100 - 5000 μeV	1 - 60	0.4 - 3	150 - 1000
Thermal neutrons	5 - 50 meV	60 - 600	0.13 - 0.4	1000 - 4000
Hot neutrons	0.05 - 0.5 eV	600 - 6000	0.04 - 0.13	4000 - 10000

The neutron

As a probe

- Wavelengths on the scale of inter-atomic distances: $Å$ - nm wavelengths to measure $Å$ - μm distances/sizes

$$n\lambda = 2dsin\Theta$$

- Energies comparable to structural and magnetic excitations: *meV* neutrons to measure *neV – meV* energies

- Neutral particle – gentle probe - no radiation damage, highly penetrating (e.g. 30 cm of Al)

- Magnetic moment (nuclear spin) probes magnetism of unpaired electrons (N.B. μ_e ~ 1000x μ_N)

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THE NEUTRON

As a probe − **interacting with matter − scattering from atoms**

Neutron flux at reactor core

- 1.5×10^{15} n/cm^2/s

Flux at an instrument sample position

- 10^8 n/cm^2/s

$\rightarrow 10^{-6}$ n/μm^2/μs

$\rightarrow 10^{-15}$ n/nm^2/ns

On these time and length scales, neutrons are being scattered one at a time

Need wave-particle duality of neutrons

interference pattern
in front of detector

spherical waves
emitted by
scattering centres

source

plane waves in
scattering system

NEUTRONS
FOR SOCIETY

THE NEUTRON

As a probe – interacting with matter – **(elastic) scattering from a single fixed nucleus**

$$-b\, \frac{e^{i\mathbf{k}_f \cdot \mathbf{r}}}{r}$$

- Nuclear size « neutron wavelength → point-like s-wave scattering

- *b* is the scattering length ('power') in *fm*

- #neutrons scattered per second per unit solid angle Ω: $\Psi^2 r^2 d\Omega$

$$d\sigma/d\Omega = b^2$$

- σ is the cross-section: $4\pi b^2$ (in barns)

$$V(\mathbf{r}) = \frac{2p\hbar^2}{m_r}\, b\, d(\mathbf{r})$$

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THE NEUTRON

As a probe – interacting with matter – **scattering from a set of nuclei**

$$\frac{d\sigma}{d\Omega} = \sum_{j,k} b_j b_k e^{i\vec{Q}.\left(\vec{R}_j - \vec{R}_k\right)}$$

$$\vec{Q} = \vec{k}_f - \vec{k}_i$$

- Q is called momentum transfer
- Q-dependence (eg angle) gives info about atomic positions

spherical waves emitted by scattering centres

interference pattern in front of detector

source

plane waves in scattering system

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THE NEUTRON

As a probe – interacting with matter – **scattering from a set of identical nuclei – coherent and incoherent scattering**

- Set of *N* similar atoms/ions – spins/isotopes are *uncorrelated* at different sites
- *b* depends on spin/isotope

- Average is ‹*b*›

- Incoherent scattering gives a *Q* independent (flat) background

- But it can be useful to probe the dynamics of single particles (later)

$$\frac{d\sigma}{d\Omega} = \langle b \rangle^2 \sum_{j,k} e^{iQ \cdot (R_j - R_k)} + \left(\langle b^2 \rangle - \langle b \rangle^2 \right) N$$

$$\sigma_{coh} = 4\pi \langle b \rangle^2 \qquad\qquad \sigma_{coh} = 4\pi b_{coh}^{\ 2}$$

$$\sigma_{incoh} = 4\pi \left(\langle b^2 \rangle - \langle b \rangle^2 \right) \qquad \sigma_{incoh} = 4\pi b_{inc}^{\ 2}$$

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The neutron

As a probe – interacting with matter – **scattering from a set of identical nuclei – coherent and incoherent scattering**

- If single isotope and zero nuclear spin, no incoherent scattering

- If single isotope and non-zero nuclear spin I ('spin incoherence')

- nucleus+neutron spin: $I+1/2$ and $I-1/2$ scattering length b^+ and b^-

- To reduce incoherent scattering (background):

  – polarise nuclei and neutrons

  – use isotope substitution e.g. H$\rightarrow$ D

$$\langle b \rangle = \frac{1}{2I+1}\left[(I+1)b^+ + Ib^-\right]$$

$$\langle b^2 \rangle - \langle b \rangle^2 = \frac{I(I+1)}{(2I+1)^2}\left(b^+ - b^-\right)^2$$

NEUTRONS
FOR SOCIETY

Scattering lengths

Light atoms

Contrast

THE NEUTRON

Scattering lengths can be positive or negative (nuclear physics)

- Positive *b* (most nuclei): phase change

- Negative *b*: no phase change at scattering point

ZSymbA	p or $T_{1/2}$	I	b_c	b_+	b_-	c	σ coh	σ inc	σ scatt	σ abs
0-N-1	10.3 MIN	1/2	-37.0(6)	0	-37.0(6)		43.01(2)		43.01(2)	0
1-H			-3.7409(11)				1.7568(10)	80.26(6)	82.02(6)	0.3326(7)
1-H-1	99.985	1/2	-3.7423(12)	10.817(5)	-47.420(14)	+/-	1.7583(10)	80.27(6)	82.03(6)	0.3326(7)
1-H-2	0.0149	1	6.674(6)	9.53(3)	0.975(60)		5.592(7)	2.05(3)	7.64(3)	0.000519(7)
1-H-3	12.26 Y	1/2	4.792(27)	4.18(15)	6.56(37)		2.89(3)	0.14(4)	3.03(5)	< 6.0E-6
2-He			3.26(3)				1.34(2)	0	1.34(2)	0.00747(1)
2-He-3	0.00013	1/2	5.74(7)	4.374(70)	9.835(77)	E	4.42(10)	1.532(20)	6.0(4)	5333.0(7.0)
2-He-4	0.99987	0	3.26(3)				1.34(2)	0	1.34(2)	0
3-Li			-1.90(3)				0.454(10)	0.92(3)	1.37(3)	70.5(3)
3-Li-6	7.5	1	2.0(1)	0.67(14)	4.67(17)	+/-	0.51(5)	0.46(5)	0.97(7)	940.0(4.0)
3-Li-7	92.5	3/2	-2.22(2)	-4.15(6)	1.00(8)	+/-	0.619(11)	0.78(3)	1.40(3)	0.0454(3)

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The neutron

Scattering lengths can be positive or negative
→ **Contrast matching**

THE NEUTRON

As a probe – interacting with matter - **absorption**

- Absorption – neutron capture

- Several strong absorbers:

   He, Li, B, Cd, Gd,…

- Isotope dependent – choose to your advantage

The neutron

- How to detect a weakly interacting, neutral particle?

- With a neutron absorber and measure the resulting signal

$$^3_2\text{He} + {}^1_0\text{n} \rightarrow {}^3_1\text{H} + p + 0.764 \text{ MeV}$$

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THE NEUTRON

Scattering and absorption cause attenuation of a neutron beam → imaging

NEUTRONS

X-RAYS

The neutron

Scattering and absorption cause attenuation of a neutron beam → imaging

THE NEUTRON

As a probe – interacting with matter - **summary**

- Interaction with nuclei:
  - short range interaction → angle independent scattering (no form factor)
  - scattering length can be <u>positive or negative</u> (→ contrast variation)
  - depends on <u>isotope</u> (→ selectivity) and <u>nuclear spin</u>
  - → <u>incoherent scattering</u> – strength (to come!) and weakness (background)
  - <u>coherent scattering</u> → interference effects → structural information
  - scattering <u>contrast</u> different from X-rays, favours light atoms
- A gentle probe - meV neutron beam does not cause radiation damage like a ~10 keV photon beam (what about XFEL!)
- Magnetic moment probes magnetism of unpaired electrons (form factor!)

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NEUTRONS AND THEIR INTERACTION WITH MATTER

Overview

- History – neutrons and nuclear reactions

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- Properties – as a particle and a probe

- **Instruments – exploiting the probe to do science**

NEUTRONS FOR SOCIETY

Time and length scales

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THE ILL'S INSTRUMENT SUITE

Optimised for continuous neutron beams

General expression for scattering from a complex system

Deriving the general scattering function

Based on

- Born approximation – kinematic theory: neutron wavefunction un-perturbed inside sample

- Fermi's Golden Rule to calculate transitions of neutron (k) and system/sample (λ) from initial to final states

- Hamiltonian to describe the system states (λ)

$$\frac{d\sigma}{d\Omega} = \frac{\sum\limits_{k_f\,in\,d\Omega} W_{k_i,\lambda_i \to k_f,\lambda_f}}{\Phi\,d\Omega}$$

$$\sum_{k_f\,in\,d\Omega} W_{k_i,\lambda_i \to k_f,\lambda_f} = \frac{2\pi}{\hbar}\rho_{\mathbf{k}_f}\left|\left\langle \mathbf{k}_f\lambda_f|V|\mathbf{k}_i\lambda_i\right\rangle\right|^2$$

$$\left(\frac{d^2\sigma}{dE_f\,d\Omega}\right)_{\lambda_i\to\lambda_f} = \frac{k_f}{k_i}\left(\frac{m_n}{2\pi\hbar^2}\right)^2\left|\left\langle \mathbf{k}_f\lambda_f|V|\mathbf{k}_i\lambda_i\right\rangle\right|^2\delta\left(E_i-E_f+E_{\lambda_i}-E_{\lambda_f}\right)$$

General expressions for scattering from a set of moving atoms

Deriving the scattering function – end up with (after much algebra and manipulations!)

$$\left(\frac{d^2\sigma}{dEd\Omega}\right) = \frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{jk} b_j b_k \int_{-\infty}^{+\infty}\left\langle \exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_k(t)\right\}\right\rangle \exp(i\omega t)dt$$

$$\left(\frac{d^2\sigma}{dEd\Omega}\right) = \frac{k_f}{k_i}\frac{1}{2\pi\hbar}S(\vec{Q},\omega)$$

- Beam and sample are 'separated'

- Experiment measures double differential cross-section which is simply related to $S(Q,\omega)$ (or $I(Q,t)$) describing the sample

- $S(Q,\omega)$ is the double Fourier transform of the time-dependent pair-correlation function $G(r,t)$

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General expressions for scattering from a set of moving atoms

Deriving the scattering function – end up with – **coherent & incoherent contributions**

- For a simple system with a single element but different *b*'s

$$\frac{d^2\sigma}{d\Omega dE_f}\bigg)_{coh} = \frac{\sigma_{coh}}{4\pi}\frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{jk}\int_{-\infty}^{+\infty}\left\langle\exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_k(t)\right\}\right\rangle\exp(-i\omega t)dt$$

$$\frac{d^2\sigma}{d\Omega dE_f}\bigg)_{incoh} = \frac{\sigma_{incoh}}{4\pi}\frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{j}\int_{-\infty}^{+\infty}\left\langle\exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_j(t)\right\}\right\rangle\exp(-i\omega t)dt$$

- Scattering function determined by positions *R* of different atoms at different times *t*
- Incoherent scattering can be useful: it measures the correlation between the same atom at different times → single particle dynamics - diffusion

General scattering experiment

Scattering triangle – handling Q and ω

- $\mathbf{Q} = \mathbf{k}_f - \mathbf{k}_i$, $\hbar\omega = E_f - E_i$ ($E \sim k^2$, $k = 2\pi/\lambda$)

- Elastic scattering:
  vary Q without changing ω
  $E_i = E_f$ vary 2Θ *(monochromatic)*
  vary $|E|$ fix 2Θ *(t.o.f.)*

- Quasi/in-elastic scattering:
  vary ω, normally Q will also change
  vary E_i or E_f and/or 2Θ

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GENERIC INSTRUMENT

Energy selection

- How to measure the energy of a neutron beam?
- Or, how to monochromate a beam?
- Measure λ with Bragg reflection

  $n\lambda = 2dsin\Theta$

  d = distance between scattering planes
- Use neutron *t.o.f.* (or precession of neutron magnetic moments in a magnetic field)

$$tof = \frac{L}{v} = 253\mu\sec\cdot\lambda\left[\overset{o}{A}\right]\cdot L[m]$$

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DIFFRACTION

Instruments (don't measure the final energy!) – D2b & LADI

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DIFFRACTION

Example – Formation and properties of ice XVI obtained by emptying a type sII clathrate hydrate

Extended Data Figure 2 | Diffraction patterns of Ne-filled and empty hydrate. a, b, Rietveld fit (obtained using FullProf software[*]) to diffraction pattern of empty sII D_2O hydrate (**a**) and Ne D_2O hydrate (**b**) taken at 5 K ($\lambda \approx 1.1226$ Å) on D20, ILL/Grenoble. The observed intensity is represented by open black circles, the calculated intensity as a blue line, the difference of both by a green line, grey shading marks the angular regions excluded in the refinement, red lines mark the positions of Bragg peaks of the hydrate, violet lines those of the aluminium sample can and orange lines those of ice Ic.

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DIFFRACTION

Instruments (don't measure the final energy!) – D2b & LADI

DIFFRACTION

Example – Improving drug design: HIV-1, COVID, nosocomial infection (samples ~100 µg)

Neutron crystallography reveals mechanisms used by *Pseudomonas aeruginosa* for host-cell binding

Lukas Gajdos [1,2,3], Matthew P. Blakeley [4], Michael Haertlein[1,2], V. Trevor Forsyth[1,2,5,6,7], Juliette M. Devos [1,2✉] & Anne Imberty [3✉]

- Carbohydrate-binding proteins
- LecB from *Pseudomonas aeruginosa*
- Fucose-specific lectin, medical target
- Perdeuterated protein, crystal of ~0.1 mm³
- Neutron data collected to 1.8 Å
- X-ray data collected from the same crystal
- X-ray/neutron joint refinement

European Crystallographic Association (ECA)
@ECA_social

Excited to announce that the 11th Bertaut Prize was awarded to Dr Lukáš Gajdos (@ILLGrenoble) in recognition of his exceptional research on the characterization of the interaction of lectins with sugars by neutron diffraction.

ecanews.org/blog/eleventh-…

The Eleventh ECA/ENSA
Erwin Felix Lewy Bertaut Prize

Dr. Lukáš Gajdos

SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Simplified expressions for the scattering function – coherent scattering

In previous scattering expressions

$$R=R_0+\delta R(t)$$

For normal modes: $\delta R(t)$ → displacement vectors **e** & frequencies $\boldsymbol{\omega}$

Coherent scattering - Phonons:

• Short range coupling gives long range correlations

• Dispersion as a function of **q** (or wavelength) – guitar string!

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{coh\pm1}=\frac{\sigma_{coh}}{4\pi}\frac{k_f}{k_i}\frac{(2\pi)^3}{v_0}\frac{1}{2M}\exp(-2W)\sum_s\sum_\tau\frac{\left(\vec{Q}\cdot\vec{e}_s\right)}{\omega_s}\left\langle n_s+1/2\pm1/2\right\rangle$$

$$\times\delta(\omega\mp\omega_s)\delta\left(\vec{Q}\mp\vec{q}-\vec{\tau}\right)$$

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Spectroscopy – time/frequency domain

Instruments – varying k_i & k_f – TAS, TOF

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SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Example – phonon lifetimes in thermoelectrics - Complex Metallic Alloy - $Al_{13}Co_4$ Quasicrystal approximant

[001]

Impact of structural complexity and disorder on lattice dynamics and thermal conductivity in the o-$Al_{13}Co_4$ phase

P.-F. Lory, V. M. Giordano, P. Gille, H. Euchner, M. Mihalkovič, E. Pellegrini, M. Gonzalez, L.-P. Regnault, P. Bastie, H. Schober, S. Pailhes, M. R. Johnson, Yu. Grin, and M. de Boissieu

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Example – phonon lifetimes in thermoelectrics - Complex Metallic Alloy - $Al_{13}Co_4$ Quasicrystal approximant

Spectroscopy – time/frequency domain

Simplified expressions for the scattering function – incoherent scattering

In previous scattering expressions

$$R = R_0 + \delta R(t)$$

For normal modes: $\delta R(t) \rightarrow$ displacement vectors **e** & frequencies $\boldsymbol{\omega}$

Incoherent scattering - Internal (molecular) modes:

- No long range correlations due to weak coupling

- No dispersion

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{incoh\pm 1} = \frac{k_f}{k_i}\sum_s \delta(\omega \mp \omega_s)\frac{\langle n_s + 1/2 \pm 1/2\rangle}{2\omega_s}\sum_r \frac{(\sigma_{incoh})_r}{4\pi}\frac{1}{M_r}\left|\vec{Q}\cdot\vec{e}_r\right|^2 \exp(-2W_r)$$

SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Instruments – TOF, Lagrange

Spectroscopy – time/frequency domain

Example – Kevlar (Journal of the American Chemical Society 127, 6672-6 (2005)

Spectroscopy – time/frequency domain

Example – endofullerenes

Spectroscopy – time/frequency domain

Example – endofullerenes

Spectroscopy – time/frequency domain

Instruments – Back-Scattering (QENS)

SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Example – oxide ion conductors (QENS & MD simulations)

Anode Electrolyte Cathode

Example – oxide ion conductors (QENS & MD simulations)

SPECTROSCOPY – SPIN ECHO

Energy selection - precession of neutron magnetic moments in a magnetic field (depends on t.o.f. in B)

SPECTROSCOPY – SPIN ECHO

Peng Luo [1], Yanqin Zhai [1,2], Peter Falus [3], Victoria García Sakai [4], Monika Hartl[5], Maiko Kofu [6], Kenji Nakajima [6], Antonio Faraone [7] & Y Z [1,2,8]

Magnetism

Structure and dynamics – double differential cross-section

As for interactions with nuclei but

- Neutron spin probes local magnetic fields due to electron spin and orbital contribution

- Atomic form factor – scattering from an atom is angular dependent due to electron cloud

- No incoherence effects

$$V_m = -\mu_n \cdot B = -\frac{\mu_0}{4\pi} \gamma \mu_N 2\mu_B \left\{ curl\left(\frac{s \times R}{R^2}\right) + \frac{1}{\hbar}\frac{p \times R}{R^2} \right\}$$

- N.B. σ (spin state) and V_m *(local magnetic field dependent interaction)* in these equations

$$\left(\frac{d^2\sigma}{dE_f\,d\Omega}\right)_{\sigma_i\lambda_i \to \sigma_f\lambda_f} = \frac{k_f}{k_i}\left(\frac{m_n}{2\pi\hbar^2}\right)^2 \left|\left\langle k_f\sigma_f\lambda_f \left|V_m\right| k_i\sigma_i\lambda_i\right\rangle\right|^2 \delta\left(E_i - E_f + E_{\lambda_i} - E_{\lambda_f}\right)$$

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MAGNETISM

Polarised neutrons – separate nuclear and magnetic signals & more precise information on magnetic structures

- Measure 2, 6 or 10 polarised scattering channels: u→u (non spin flip) and d→u (spin flip) in the simplest case

NEUTRONS FOR SOCIETY

MAGNETISM

Polarised neutrons – separate nuclear and magnetic signals & more precise information on magnetic structures

- Polarised (optically pumped) 3He selectively absorbs one neutron spin state – more versatile polariser

- Cryopad allows full control of incident and scattered neutron polarisation – spherical polarimetry

MAGNETISM

Example – P-T phase diagram of a multiferroic $CuFeO_2$ (Nature Communications: volume 9, Article number: 4368 (2018), crystal volume = 0.04 mm^3)

Magnetism

Example – How do electrons/spins organise in a triangular lattice? Spins pair into quantum-mechanical bonds and fluctuate...

The neutron

- Is Highly penetrating

- Interacts with nuclei – favourable for light atoms (H, Li, O,…)

- Incoherent scattering is ideal for e.g. proton dynamics

- Isotopes provide selectivity – contrast matching

- Interacts with unpaired electrons – magnetism

- Probes 15 orders of magnitude in length & 10 in time scales

Neutron sources have relatively low intensity and are only available in large scale facilities – ILL, ISIS, PSI, FRM2 in Europe, SNS & NIST in US,…

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ADDITIONAL READING

Search the web! Plus...

- ***Principles of Neutron Scattering from Condensed Matter***
- **Andrew Boothroyd (2020) Oxford University Press ISBN 9780198862314**

- *Introduction to the Theory of Thermal Neutron Scattering*
- G.L. Squires Reprint edition (1997) Dover publications ISBN 04869447

- *Experimental Neutron Scattering*
- B.T.M. Willis & C.J. Carlile (2009) Oxford University Press ISBN 978-0-19-851970-6

- *Neutron Applications in Earth, Energy and Environmental Sciences*
- L. Liang, R. Rinaldi & H. Schober Eds Springer (2009) ISBN 978-0-387-09416-8

- *Methods in Molecular Biophysiscs*
- I.N. Serdyuk, N. R. Zaccai & J. Zaccai Cambridge University Press (2007) ISBN 978-0-521-81524-6

- *Thermal Neutron Scattering*
- P.A. Egelstaff ed. Academic Press (1965)

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Vercors & Chartreuse

Mont Blanc