Magnetic or Not?
UCN Production in Solid Oxygen

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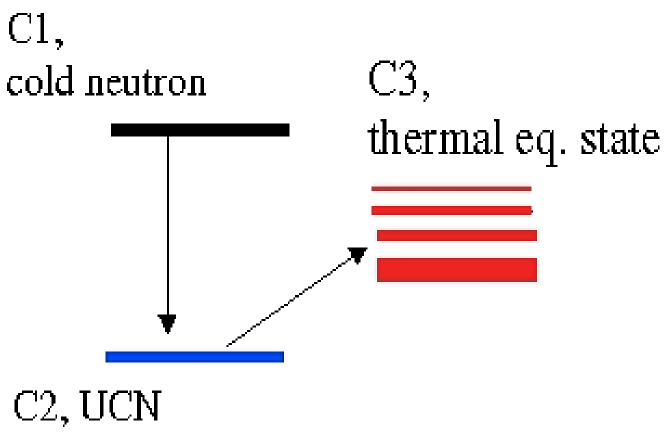
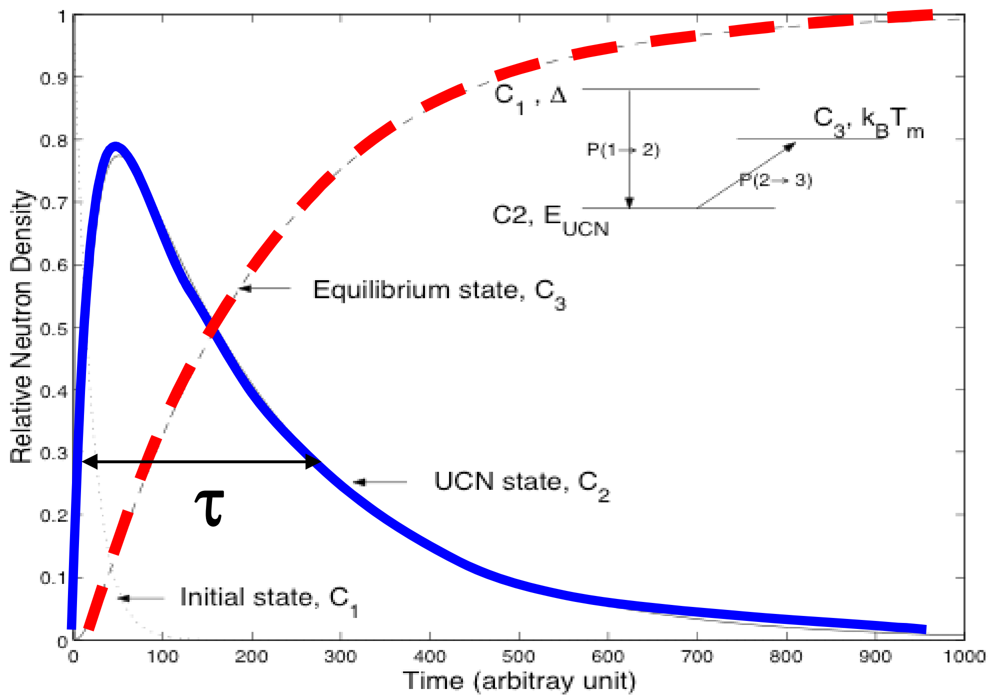
National Science Foundation
WHERE DISCOVERIES BEGIN

Dynamics of UCN Production --
Defeat thermal equilibrium





- **Lifetime of UCN in the source material, τ,** is the critical parameter to achieve large UCN densities.

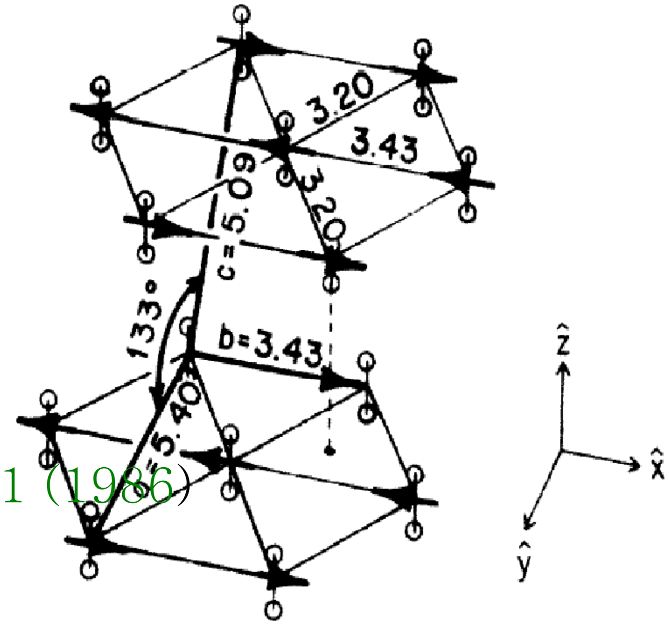
- Extract UCN out of the source before it is thermalized

  ⇒ **Spallation N source** + Seperation of the source and the storage

  \+ a UCN Valve

Solid Oxygen as a UCN Source

σ_{coh} =4.232 barn, σ_{inc} = 0 barn,
σ_{abs} = 0.0001 barn



- Electronic spin S=1 in O_2 molecules.
- Nuclear spin = 0 in $_{16}O$
- Colinear Anti-ferromagnetic in 2-D
  - α-phase, T < 24K.

P.W. Stephens and C.F. Majkrzak, Phys. Rev. B **33**, 1 (1986)

UCN Production in alpha S-O_2

- Produce UCN through magnon excitations.
  - Magnetic scattering length ~ 5.4 fm.
- Null incoherent scattering length.
- Small nuclear absorption probability.

$\Rightarrow$ A very large source possible.

Neutron Scattering in Solid O_2

- Spin(n) -Spin(e) coupling

$$V(r) = -\mu_N \cdot H = -\gamma \mu_N \sigma \cdot \{\nabla \times \frac{\mu_e \times r}{r^3}\}$$

$$V(k) = \gamma_0 \sum_l \sigma \cdot \tilde{k} \times (\tilde{S}_l \times \tilde{k}) e^{ik \cdot r_l}$$

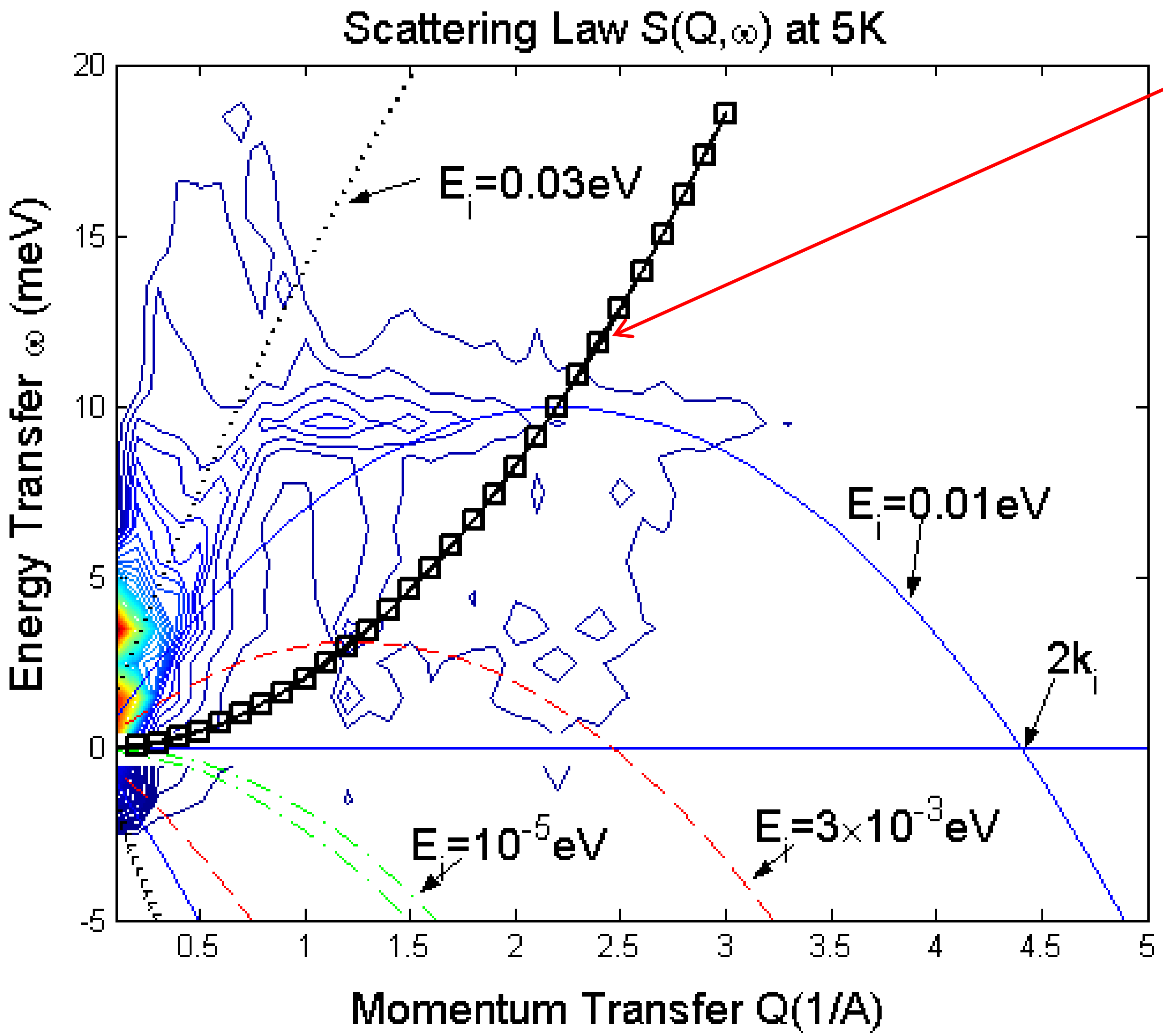
(Spin)×(Translation)

$$\frac{d^2\sigma}{d\Omega d\omega} = \left\langle \varphi_f \middle| V \middle| \varphi_i \right\rangle^2 \propto (1 - \tilde{k}_z^2) \sum_{l,l'} \left\langle \tilde{S}_l \tilde{S}_{l'} \right\rangle \times \left\langle e^{ik \cdot r_l k \cdot r_{l'}(t)} \right\rangle$$

(1+ magnon)×(1+ phonon)

→ Elastic Bragg + Magnon Scatt. + Magneto-vibrational Scatt. + both mag

Calculated S(Q,ω) in α-O2



Free Neutron Dispersion Curve

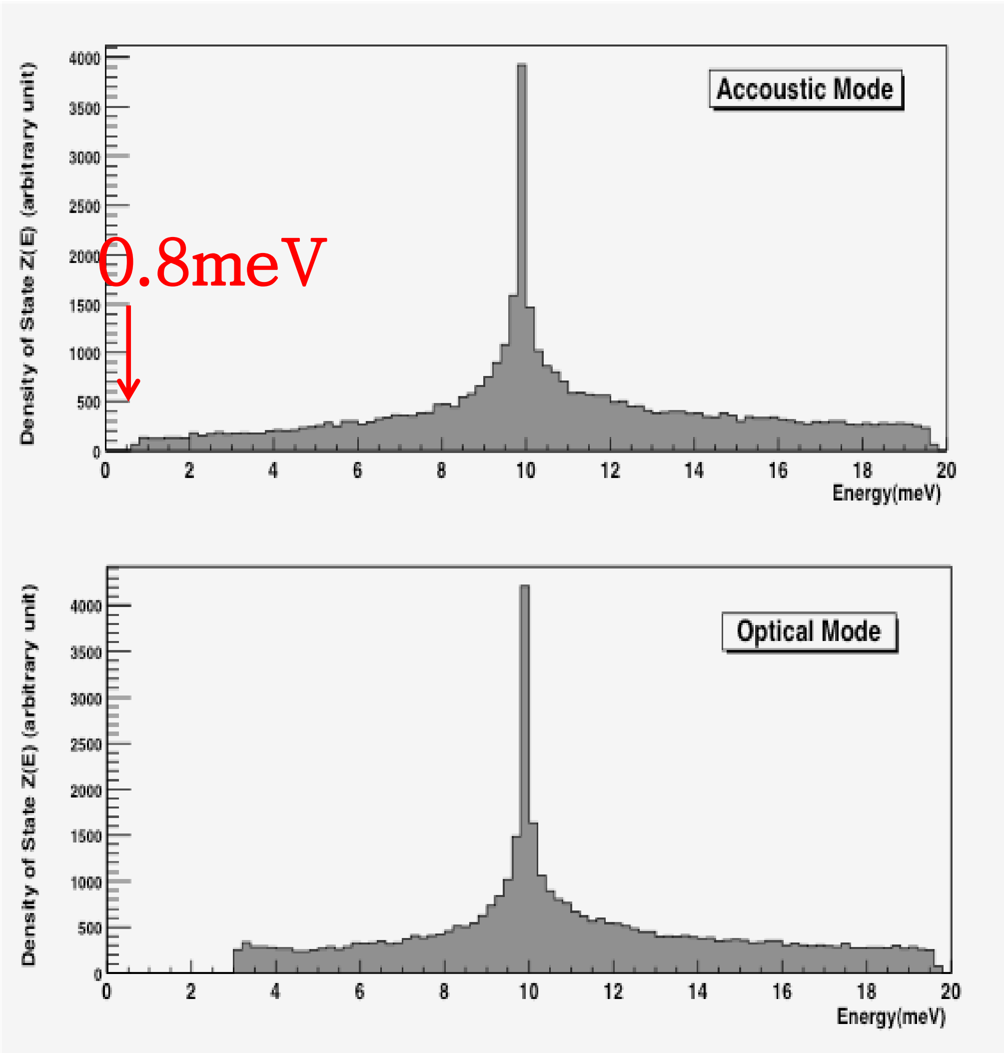
Coupling constant

Suggested in P.W. Stephens and C.F. Majkrzak, Phys. Rev. B (1986)

J_{NN}=-2.44 meV
J_{NNN} = -1.22 meV

Neutron-Magnon Scattering in S-O_2

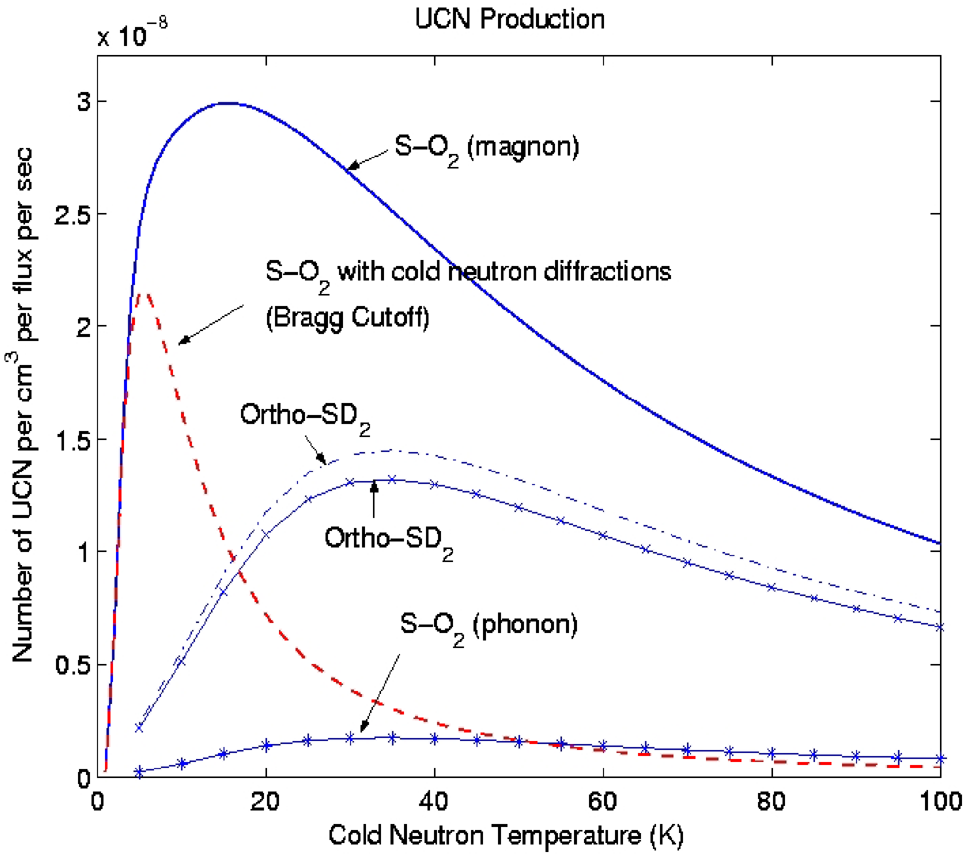
Density of States (Magnon)



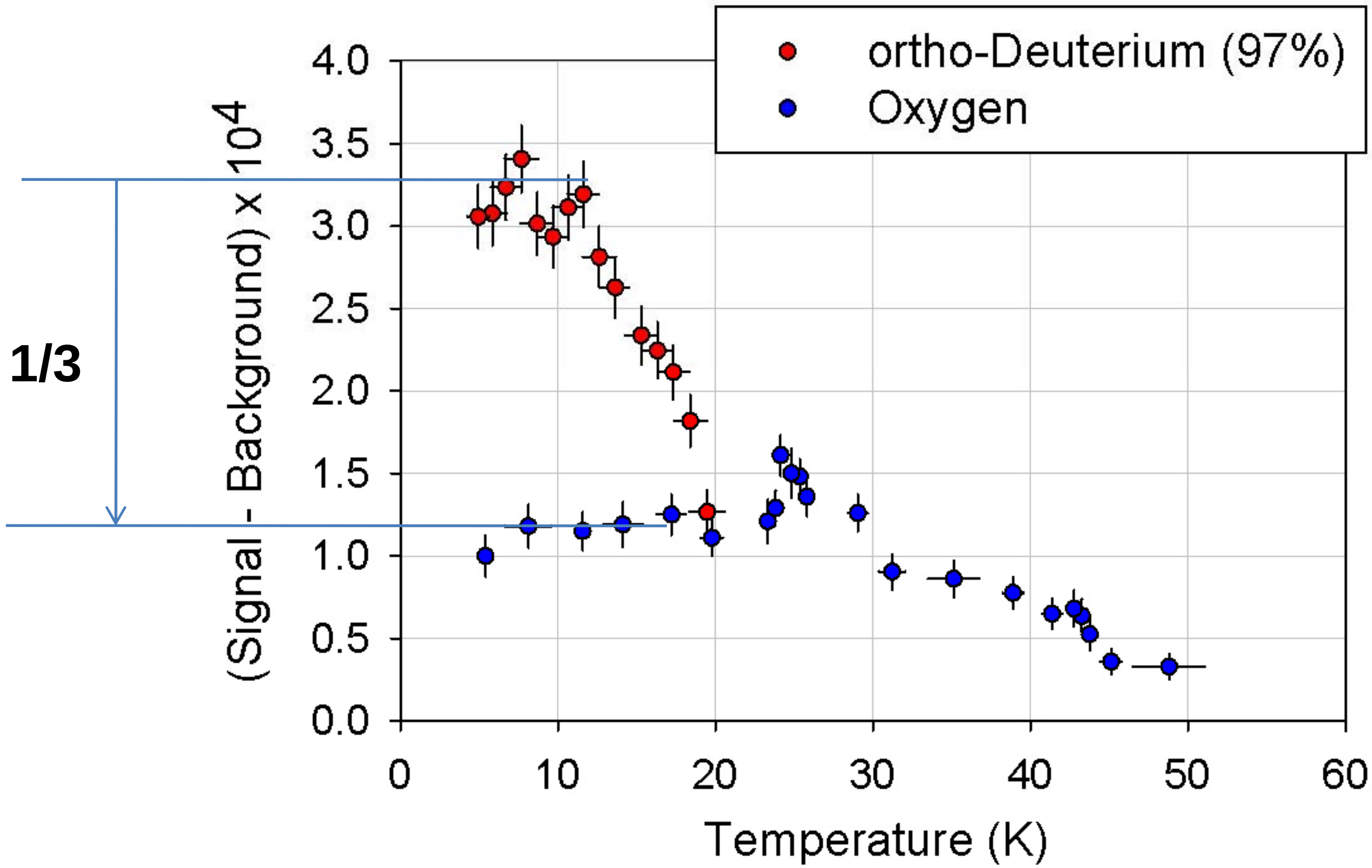
- Magnon production energy gap ~ 0.8meV
  - Magnons partially frozen at T < 8K.
  - Significantly reduce the UCN upscattering rate.

UCN production in Solid Oxygen

- Production rate
  - $P = 2.7 \times 10^{-8}\ \Phi_0$ (30K CN in S-O_2)
  - $P = 3.0 \times 10^{-8}\ \Phi_0$ (15K CN in S-O_2)
  - $P = 1.5 \times 10^{-8}\ \Phi_0$ (30K CN in S-D_2)
  - **Gain ~ 2 relative to S-D_2 (optimal)**
  - **Gain ~ 1/3 (CN scattering limited)**
- Lifetime
  - 375 ms in S-O_2
  - 40 ms in S-D_2
  - **Gain ~ 10**
- Volume gain, $(l)^n$, n= 1-3
  - l_{ucn} = 380 cm in S-O_2
  - l_{ucn} = 8 cm in S-D_2
  - **Gain ~ 50 – 10^5 (if not limited by elastic attenuation)**

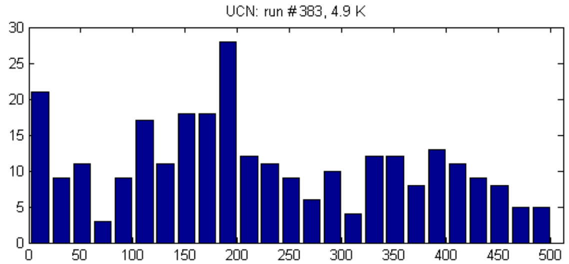


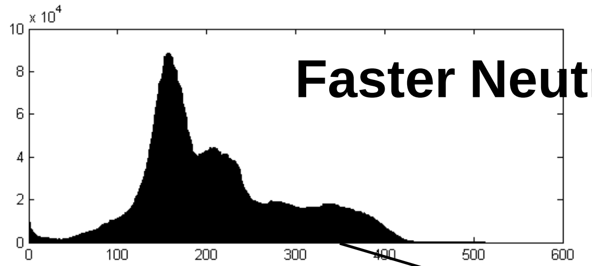
A Direct (but Naïve) Comparison between D_2 & O_2



“Bragg scattering limited” Magnon-UCN production rate
~ Phonon-UCN production rate

Varying Cold Neutron Spectrum

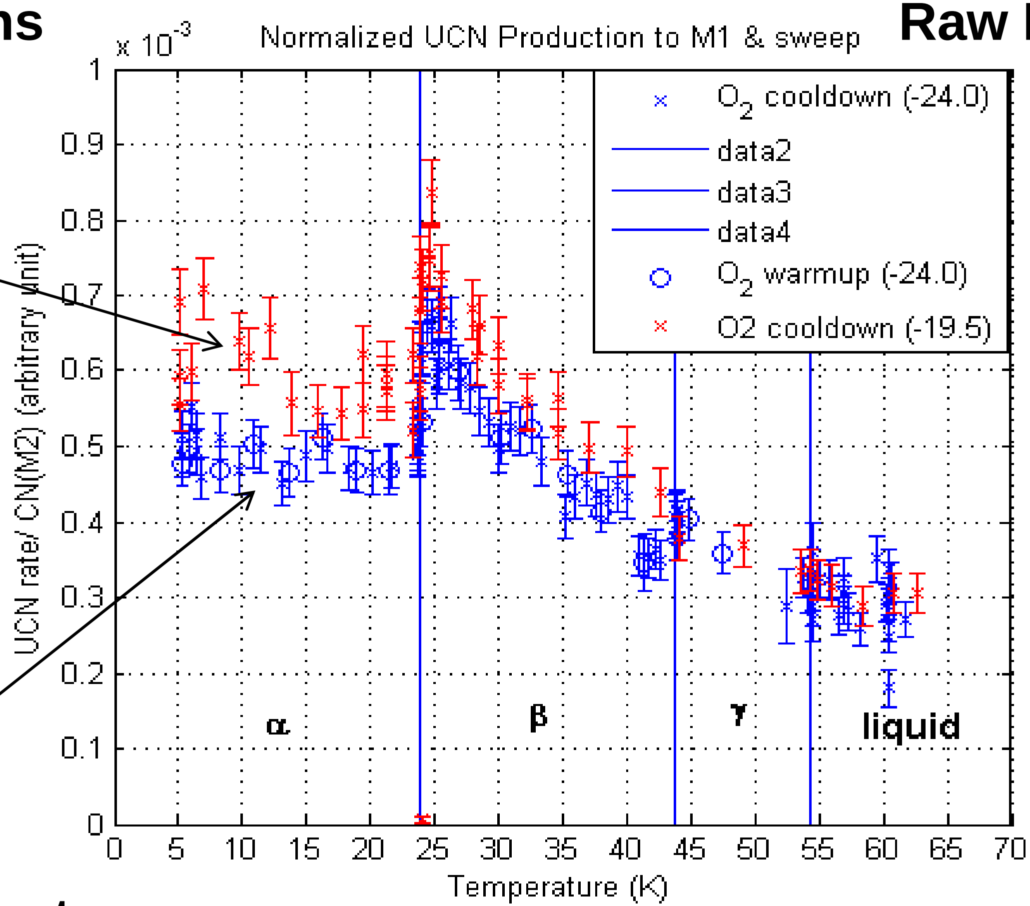


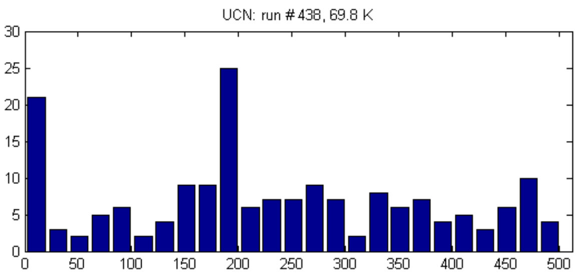


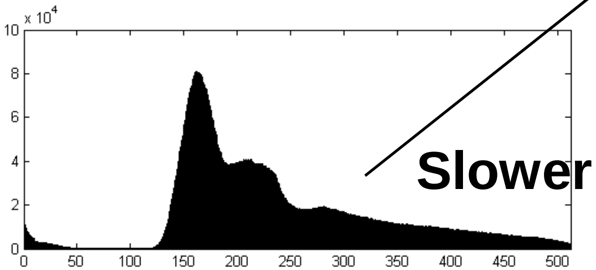
Faster Neutrons

TOF

Raw Data





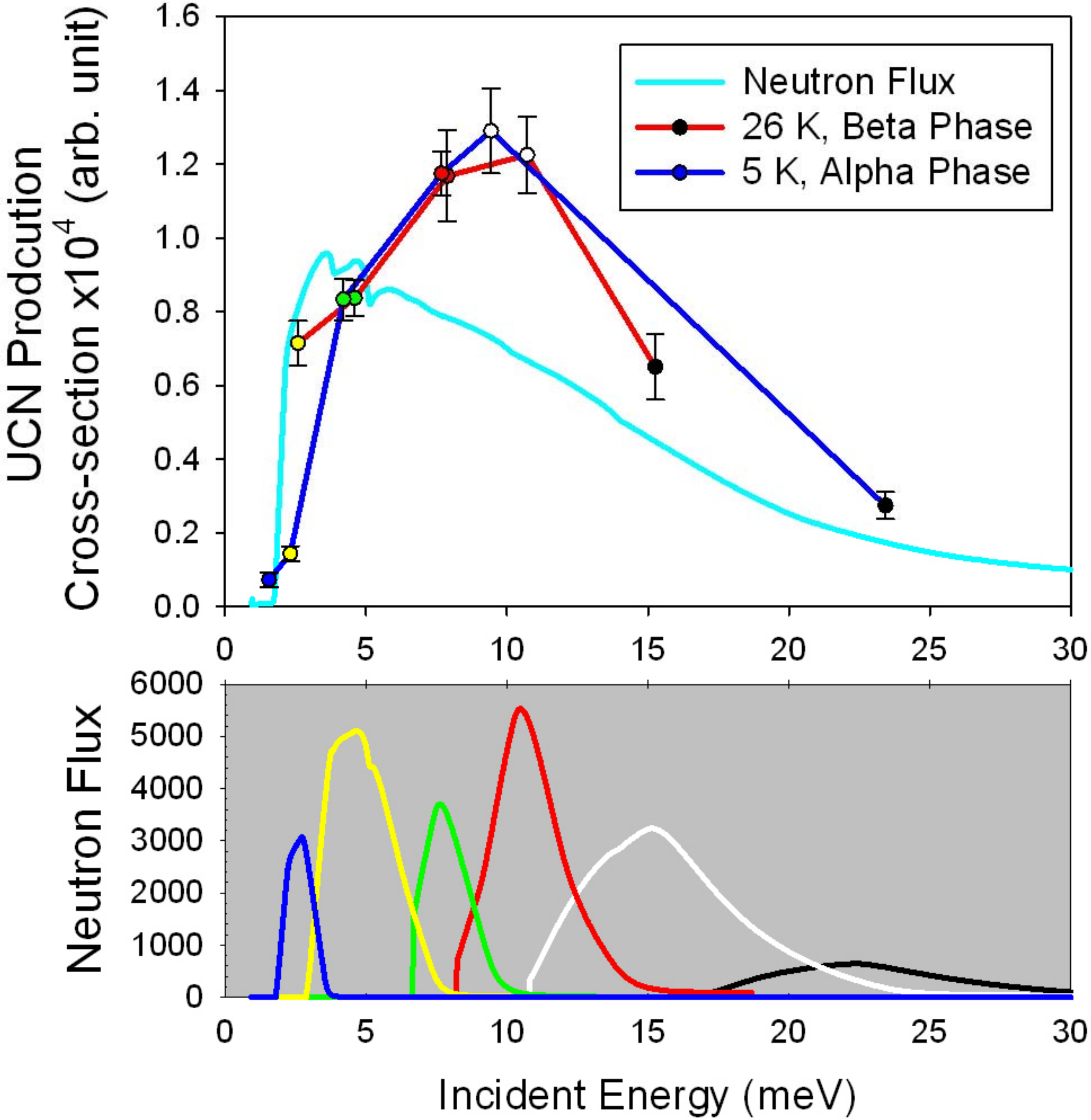


Slower Neutrons

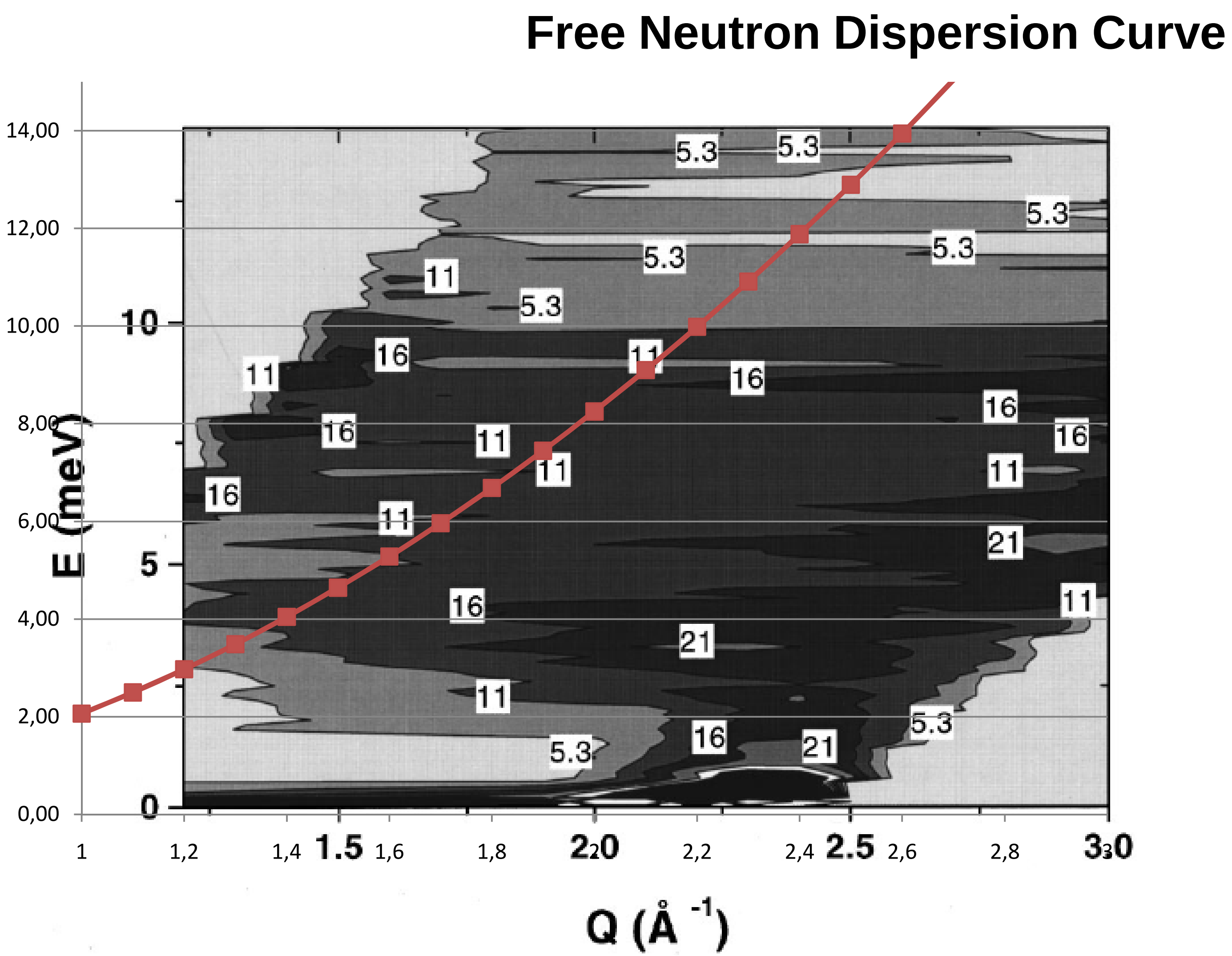
30% increase using a higher energy neutrons

Oxygen UCN Production vs. Cold Neutron Energy

Using dual frame overlap choppers in a de-phased mode

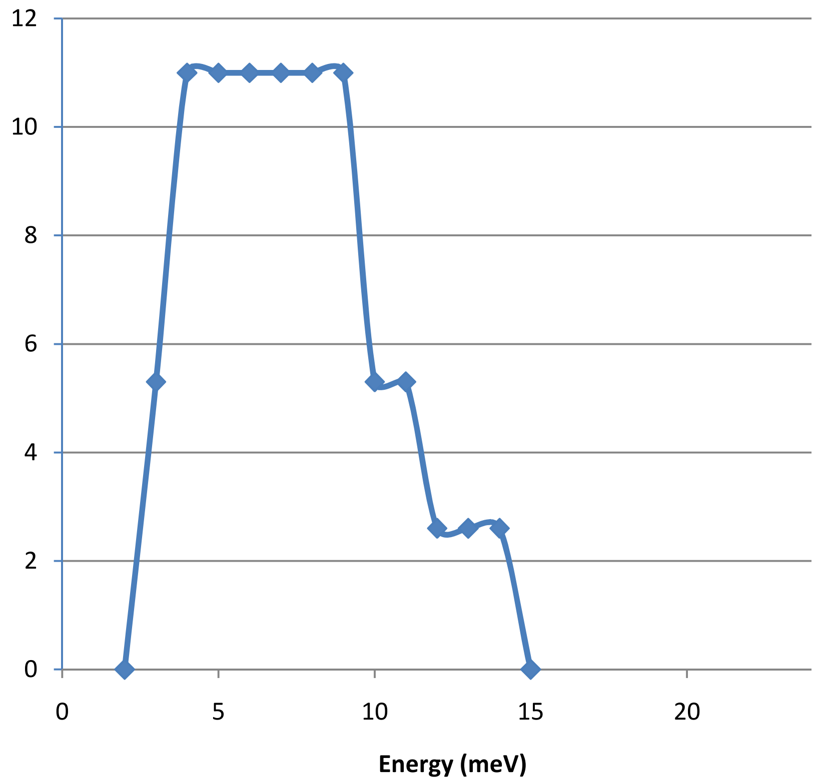


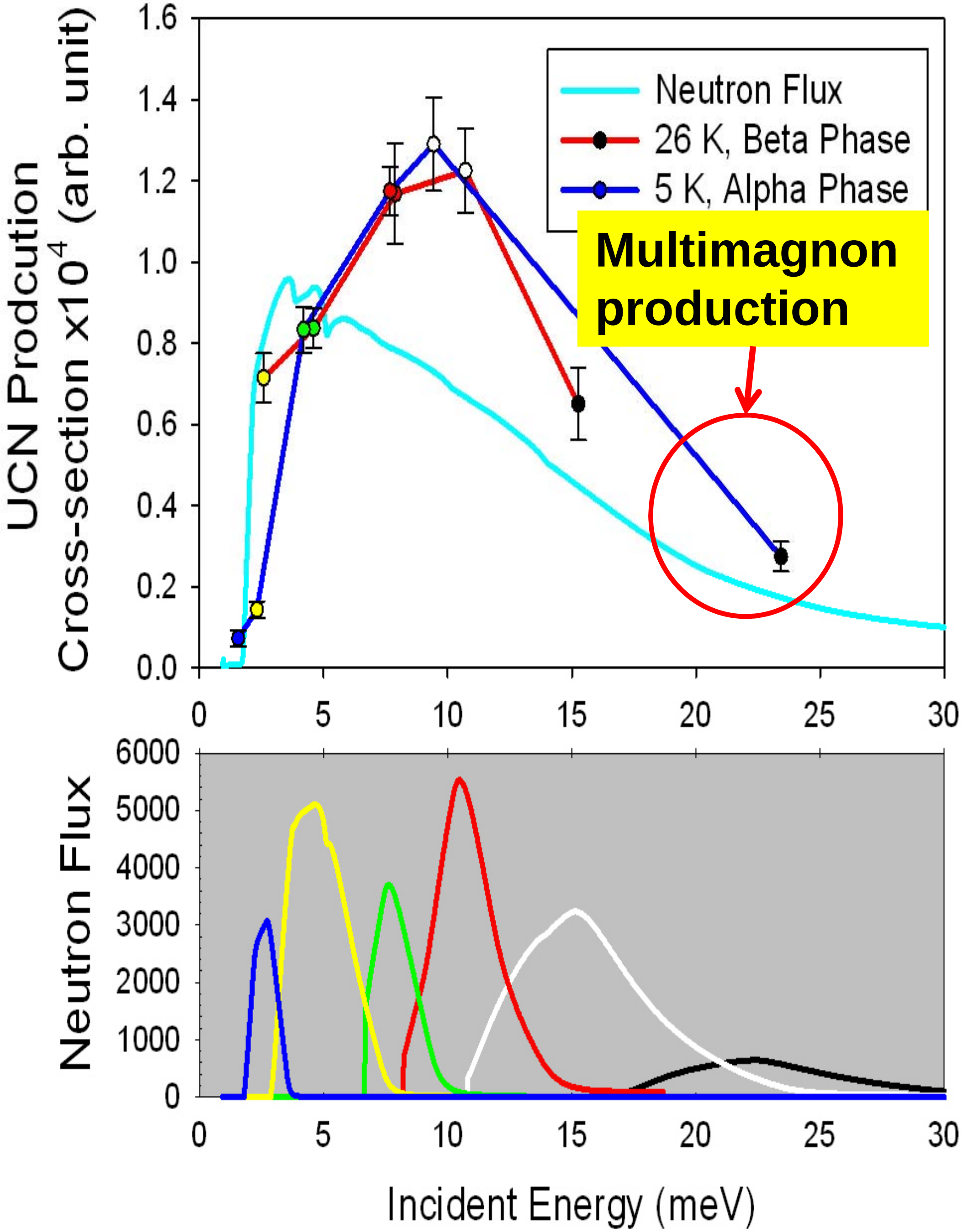
UCN Production vs S(Q,ω)

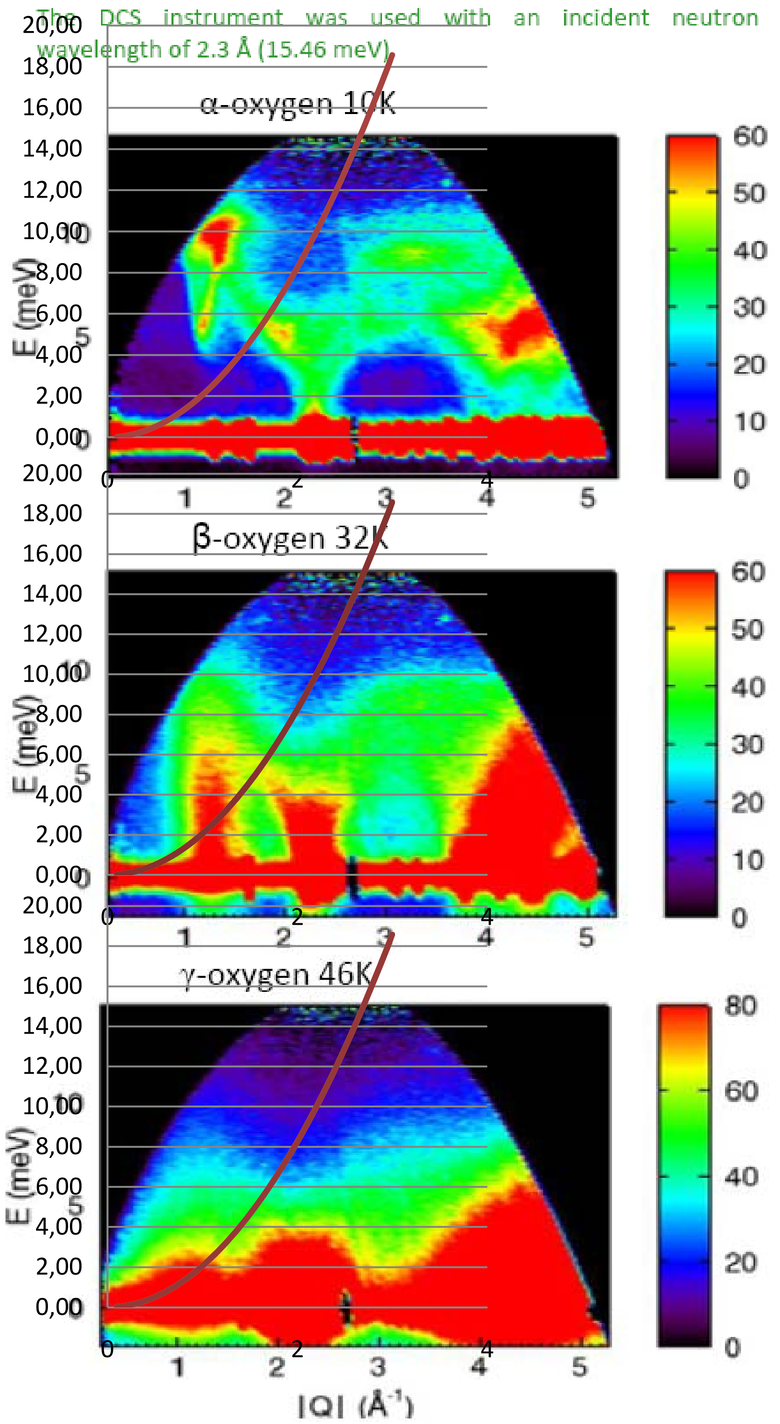


A. De Bernabe, G. J. Cuello, F.J. Bermejo, F. R. Trouw, A.P.J. Jansen, PRB, 58, 14442 (1998).

Intensity on the Free Neutron Dispersion Curve





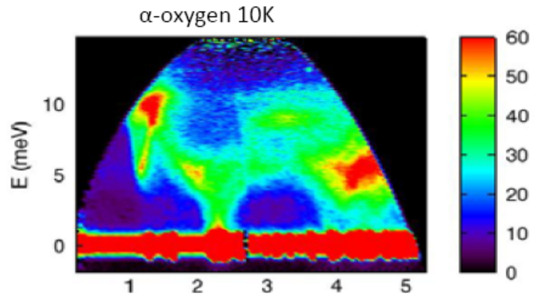


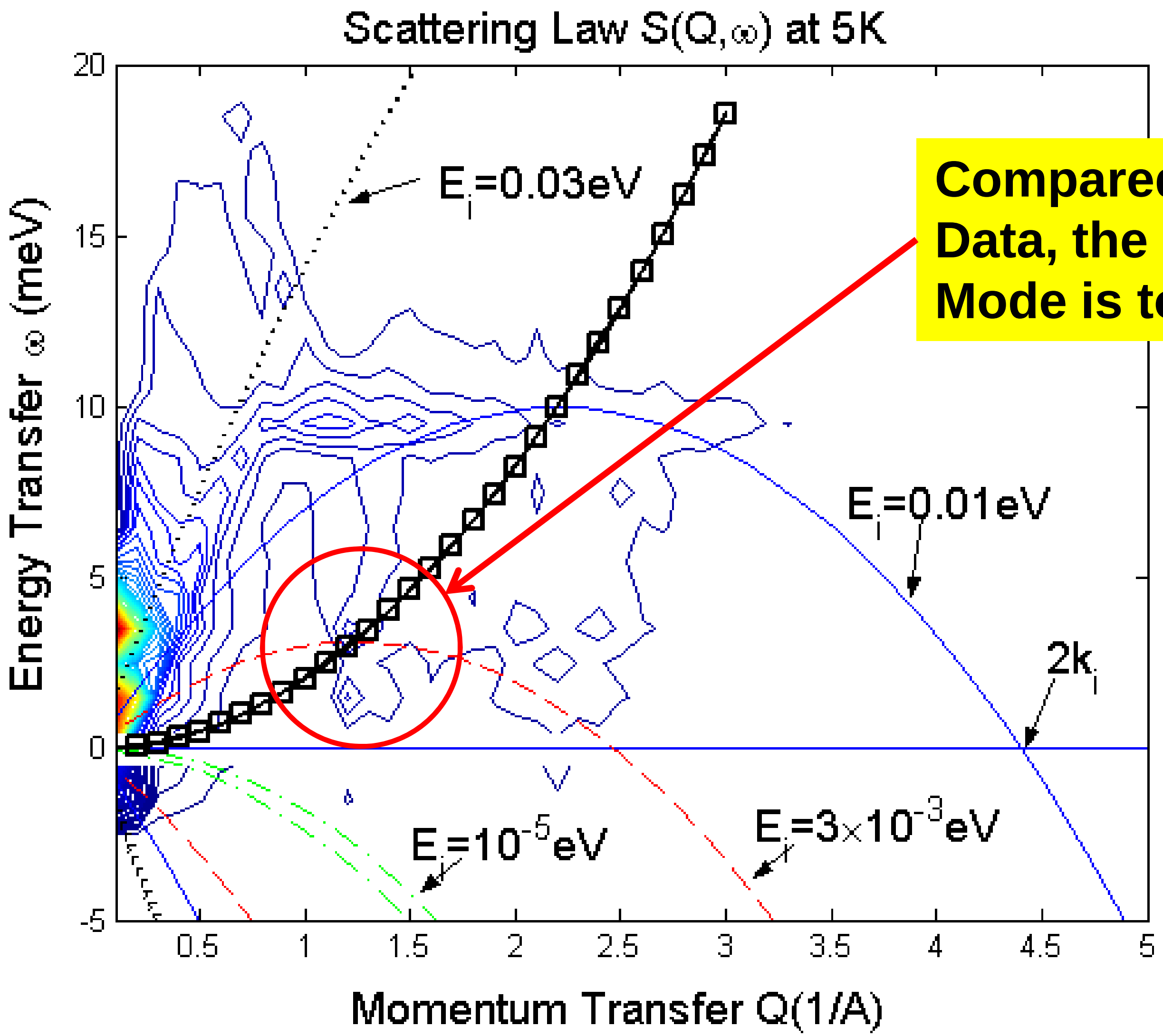
Updated S(Q,ω)

- More detailed data taken at ISIS independently confirms these results
- Origins of the "soft" modes, precursors to the long-range AF order, in beta phase needs explanations.

D. Kilburn, P.E. Sokol, C. Brown, 2008 (DCS at NIST)

Calculated S(Q,ω) in α-O_2





Compared with Data, the low energy Mode is too low!

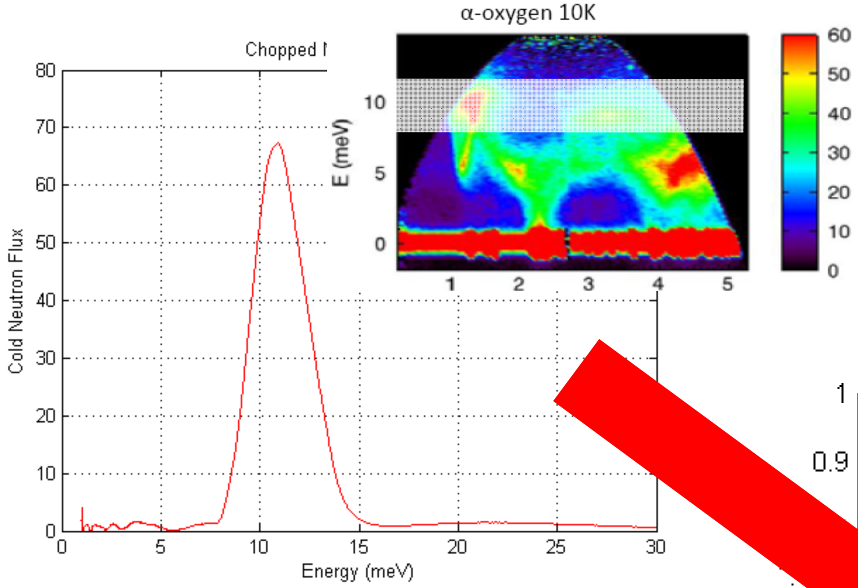
Coupling constant

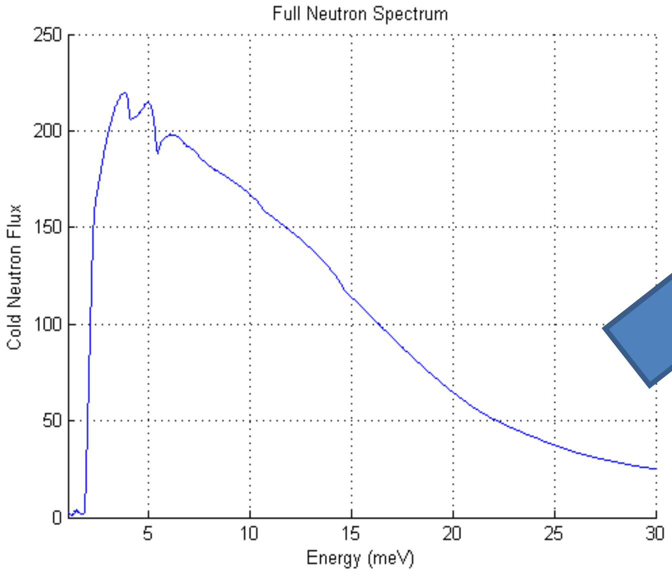
Suggested in P.W. Stephens and C.F. Majkrzak, Phys. Rev. B (1986)

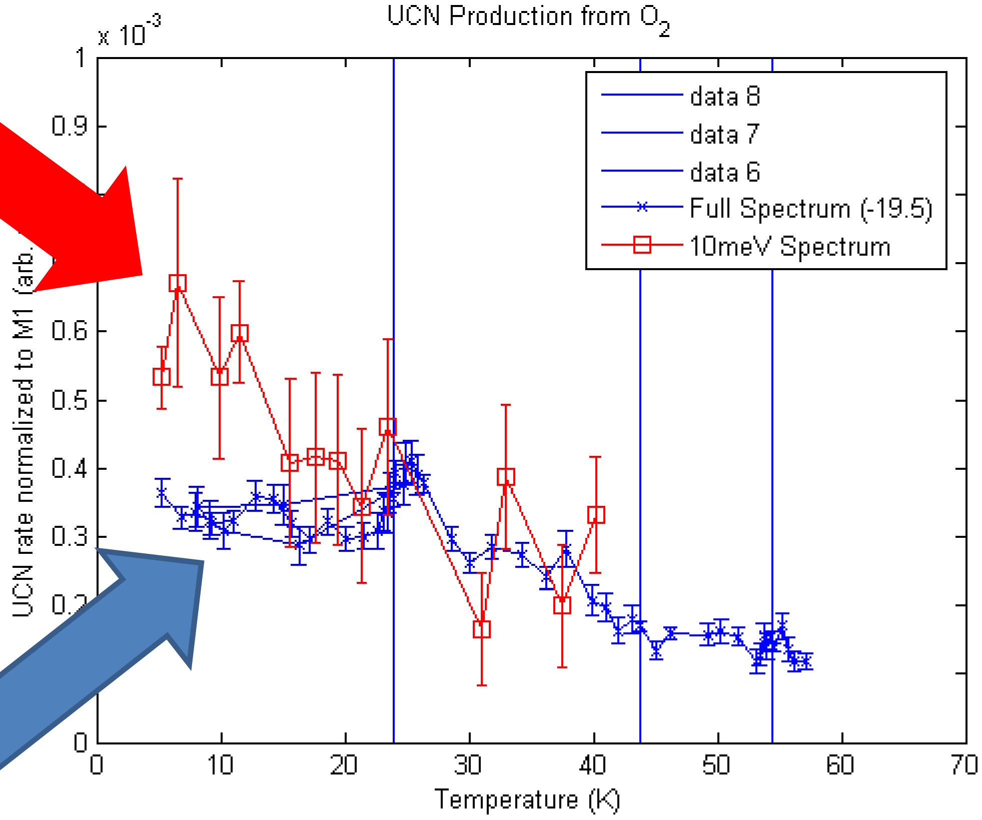
J_{NN}=-2.44 meV

J_{NNN} = -1.22 meV

UCN Production with different CN Spectrum

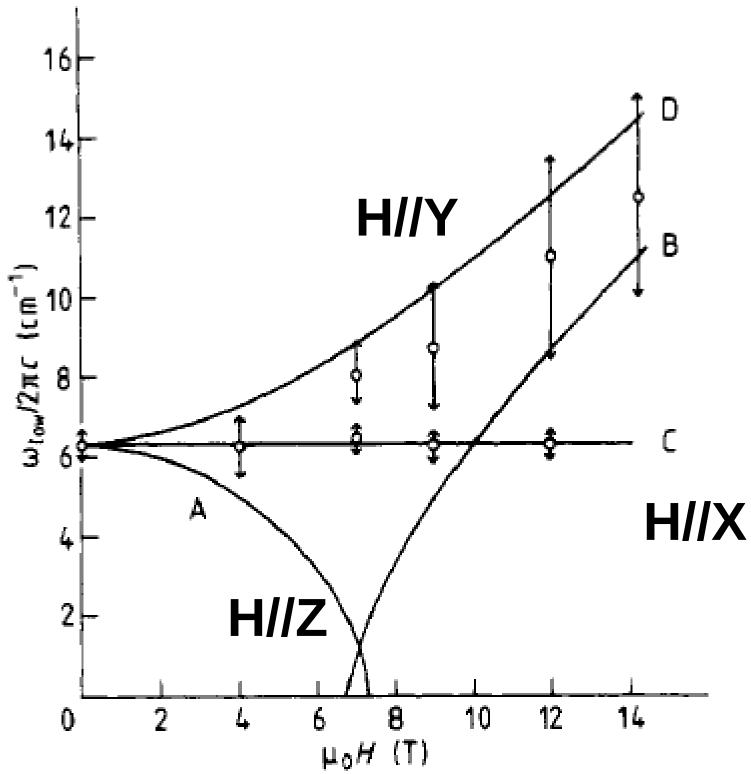


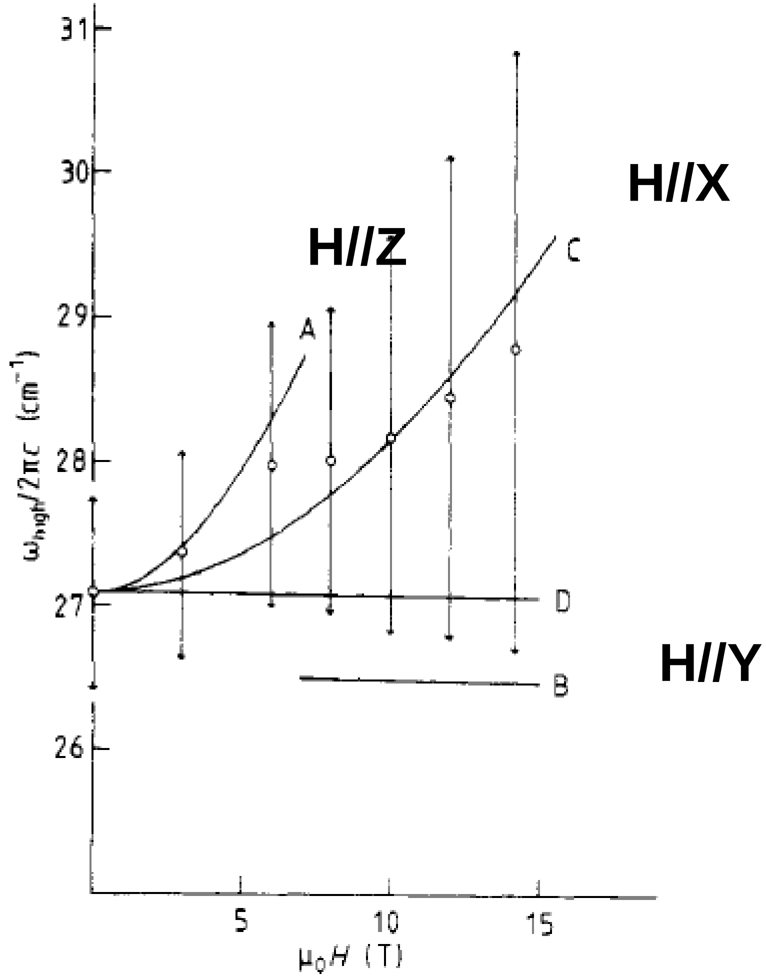




Magnetic Zeeman Splitting in α-O_2

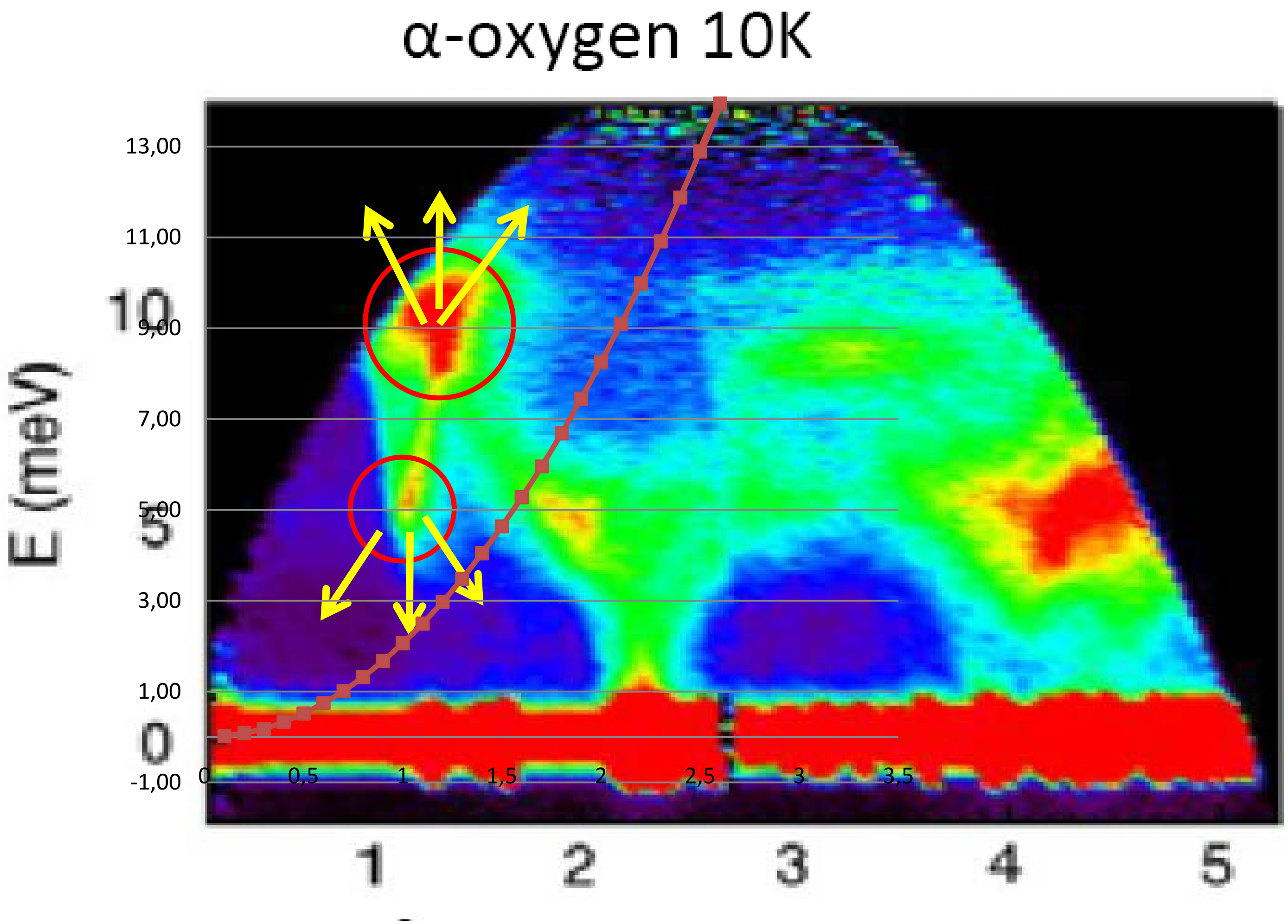
- The Low energy modes split under B field.





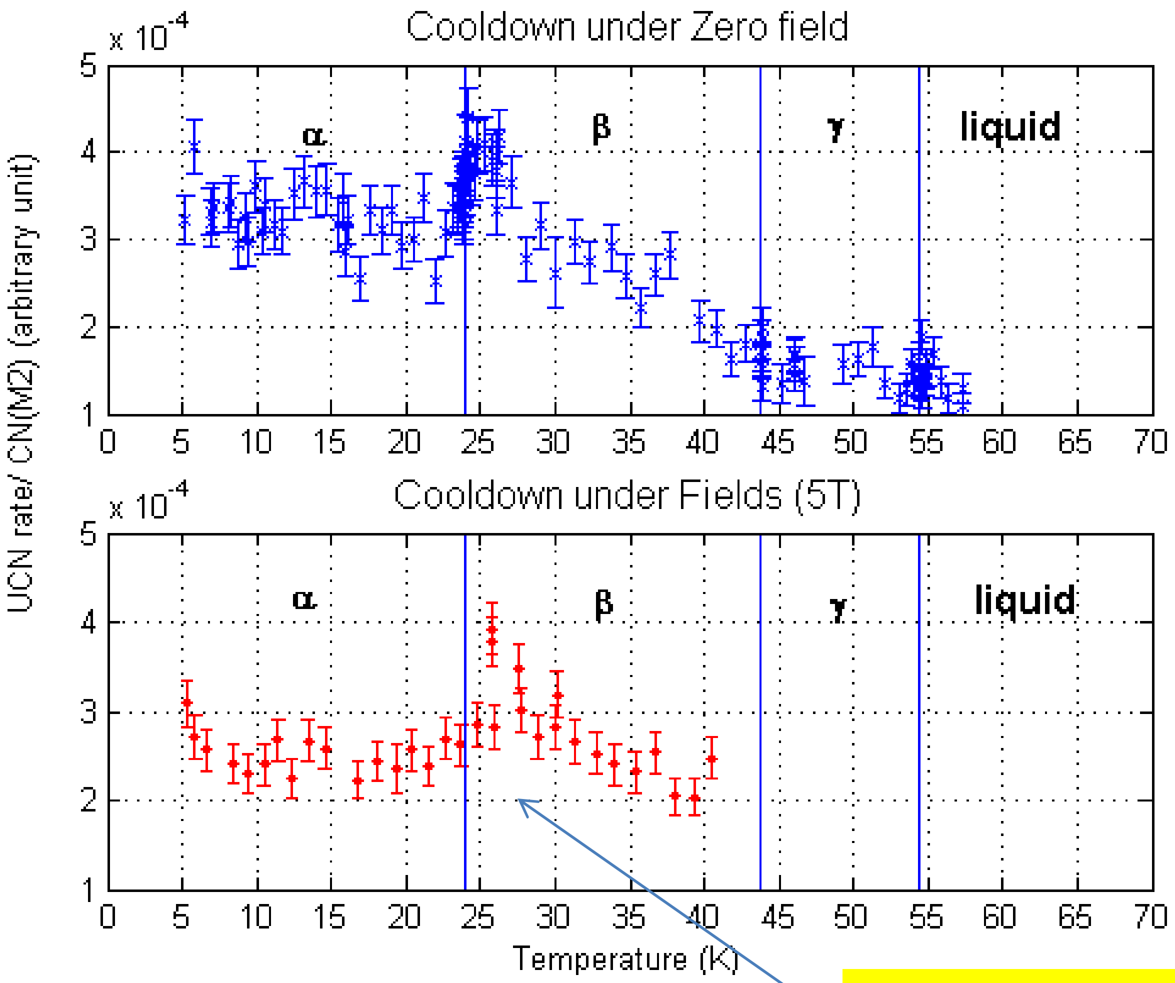
R.J. Meier, J H P Colpa, H Sigg, J. Phys. C: Solid State Phys., 17, 4501 (1984).

Magnetic Zeeman Splitting in α-O2



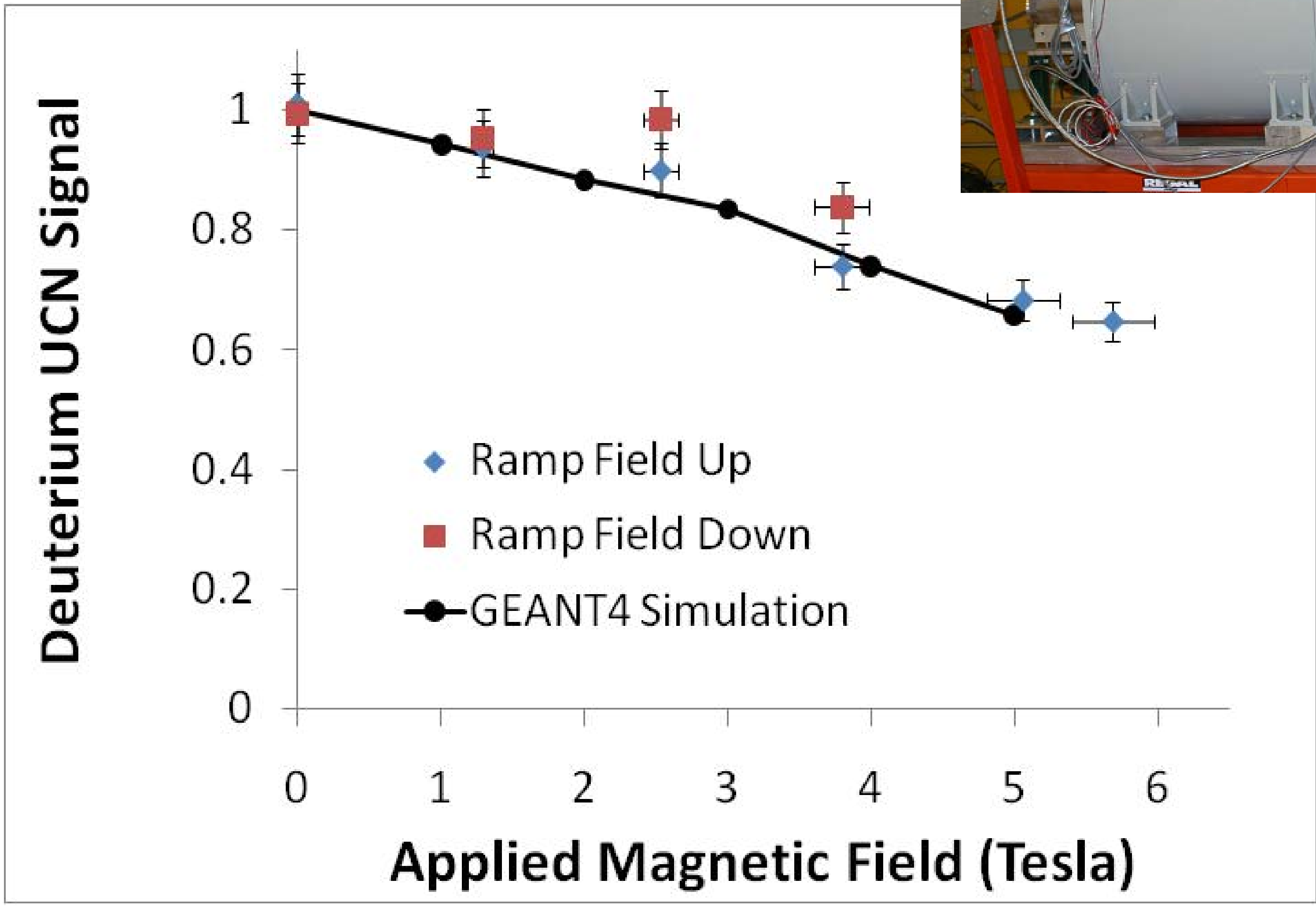
S(α,β) in B field is not yet available. We will measure it this summer.

UCN Production under B Fields

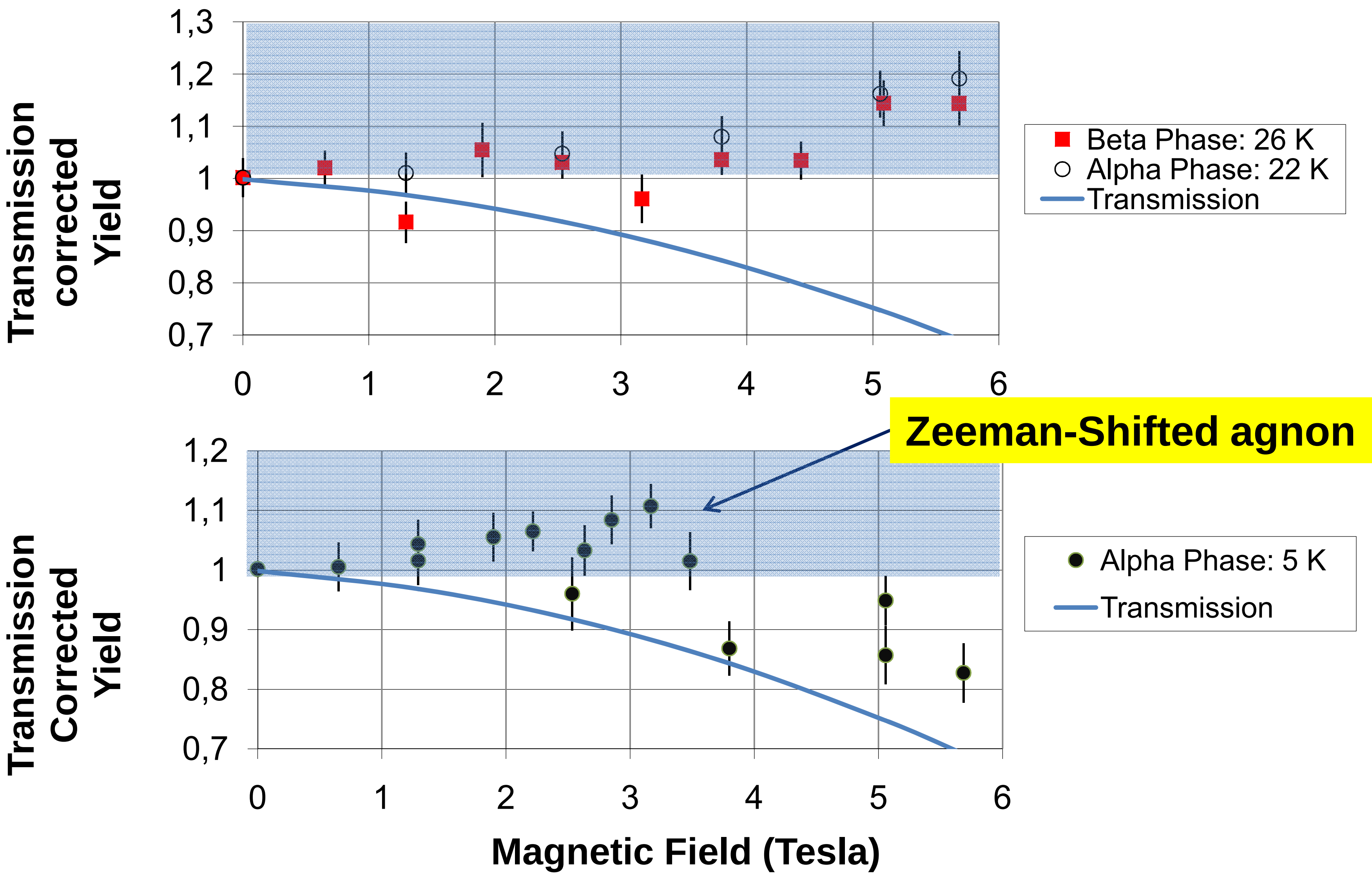


Transition Temperature Increases by ~ 2K.

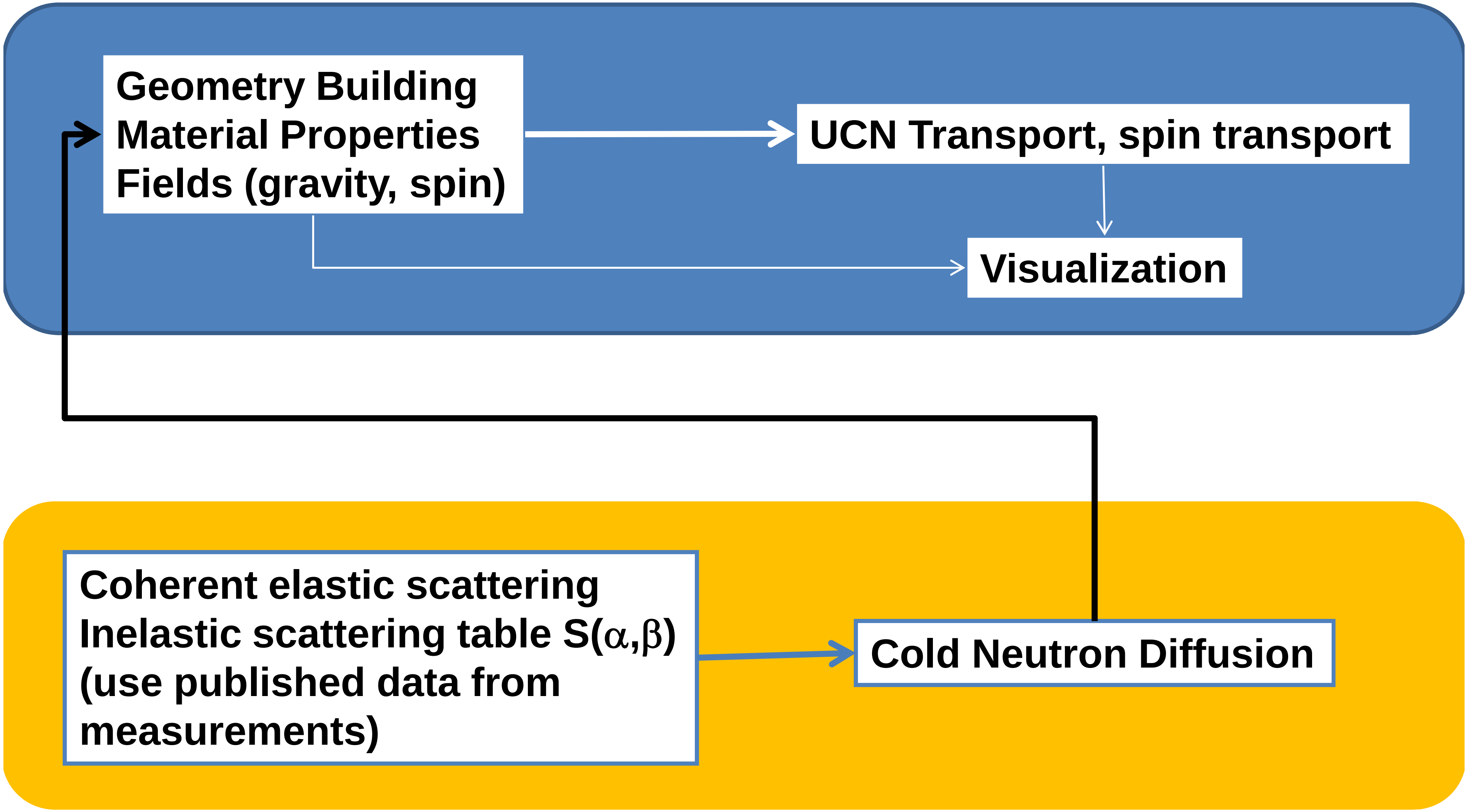
Calibration of UCN Transport with Applied Fields D_2 at 5 K



Field Dependent UCN Production in O_2

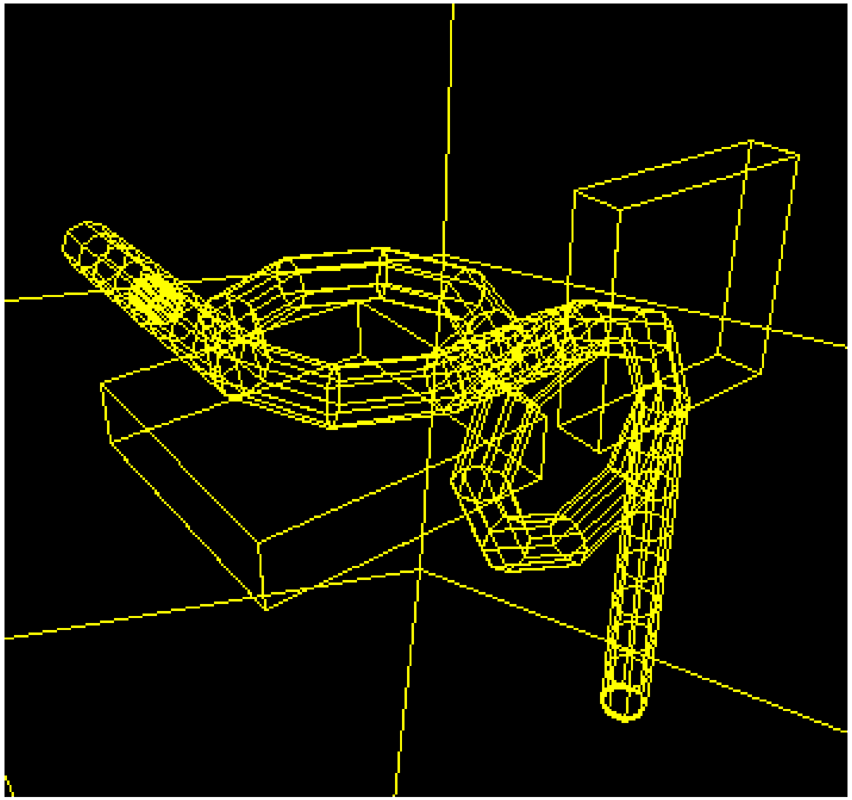


UCNTracker, a simulation suite for UCN Production & Cold Neutron Diffusion



Geometry Modeling Engine

- GUI Based
- Guide
- V = 193nEV
- Diffusivity = 0.01
- Gravity, Magnetic Field
- The Cell



The Physics in *UCNTracker*

- **UCN Optics**

$$|R|^2 = 1 - 2f\left(\frac{E\cos^2\theta}{V - E\cos^2\theta}\right)^{\frac{1}{2}}$$

- **Magnetic**

$$\frac{d}{dt}\frac{B\cdot\mu}{|B|} = 0$$

$$F = \mu\cdot\nabla B$$

- **Gravity**

$$F = mg$$

- **Scattering**

Bragg scattering
Inelastic Scattering, S(Q, ω)

Current available strategy for cold neutron simulations:

∫S(q,ω)dq = Z(ω) —*NJOY* (Incoherent approximation)→ **S'(q,ω) In ENDF** —*MCNP*→ **Cold Neutron Flux**

Limited ENDF libraries, S(q,ω) lost in translation.

Summary

- First definitive observation of UCN production using magnetic excitation.
  - The low Q soft-modes in β-O_2 are magnetic in origin.

- UCN production in α-O_2 could be a combination of inelastic magnetic and nuclear scattering.
  - Field scan indicate production enhancement ~ 10% (with large statistical uncertainties)
  - $S(Q,\omega)$ measurement under B field is planned this summer.
    - This will help to isolate the magnetic part from the nuclear part.