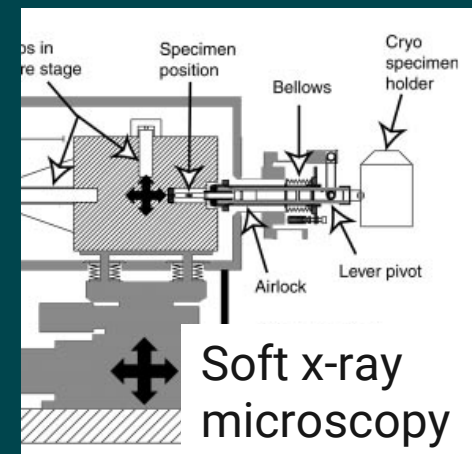
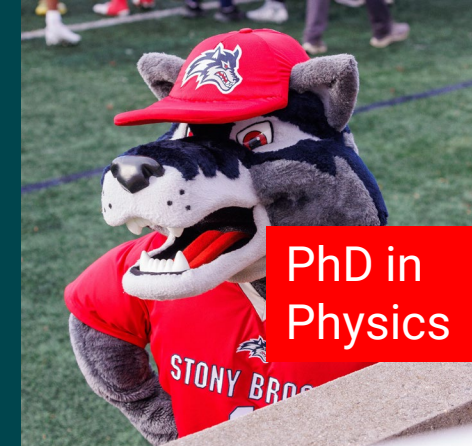
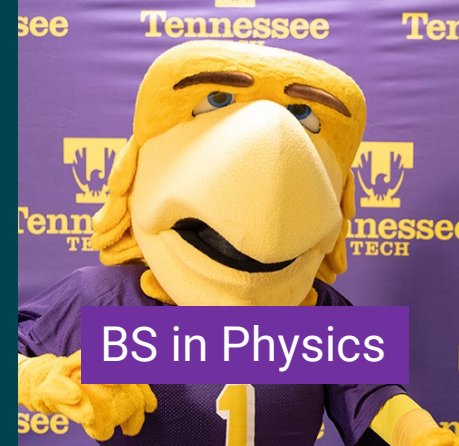


Your next speaker: Barry Winn

HYSPEC Instrument Scientist (since 2009)

- Work with users (you!) to pitch, prepare for & execute experiments
 - Sometimes tricky or unusual
- Work with a great extended team
(1.5 other instrument scientists, a scientific associate, many sample environment & instrument-related support teams, engineers & developers, & accelerator support teams)
- Co-develop fun new polarization optics, & keep the polarization nerds talking
- Never-ending quest to reduce background
- (never hurts to) request various sample environments & engage with magnet development groups & companies
- Pitch & prepare concepts for innovative neutron scattering instruments

How did this
guy get here?





Sept 2, 2026, 10:45 AM – 11:45 AM

Neutron Polarization (Contrast)

Barry Winn, NNS 2025

AND AN ARMY OF POSTER
PRESENTERS!!!!



U.S. DEPARTMENT OF
ENERGY

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

Polarized neutron scattering enables a researcher to answer important questions related to either the nuclear spin or magnetism in materials

Character

Contrast

Configuration

Capability

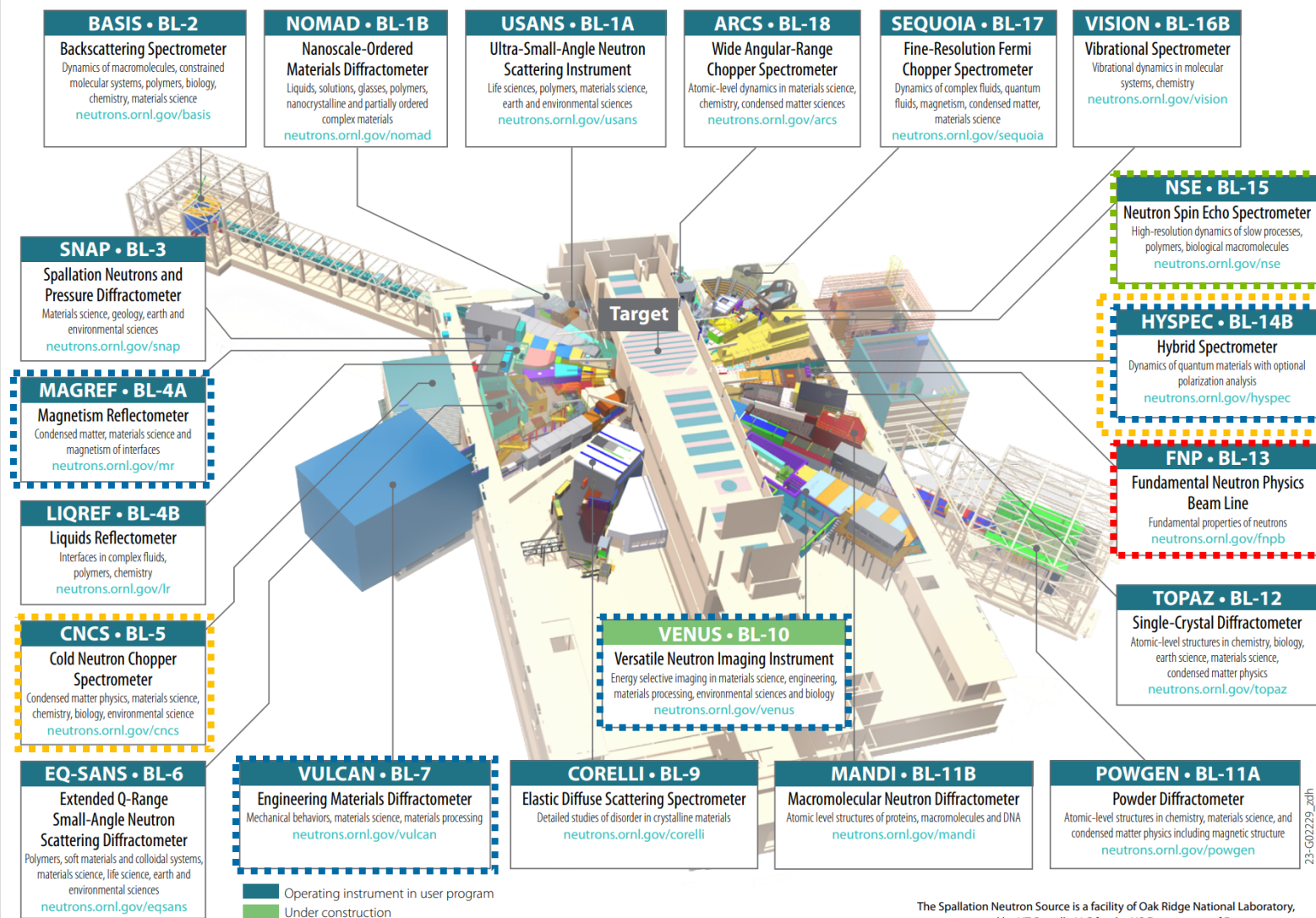
Who uses polarized neutrons at SNS?

Magnetic Moment Contrast

Nuclear Spin Contrast

Enhanced Resolution via 'Larmor' Techniques

Studies of the neutron itself



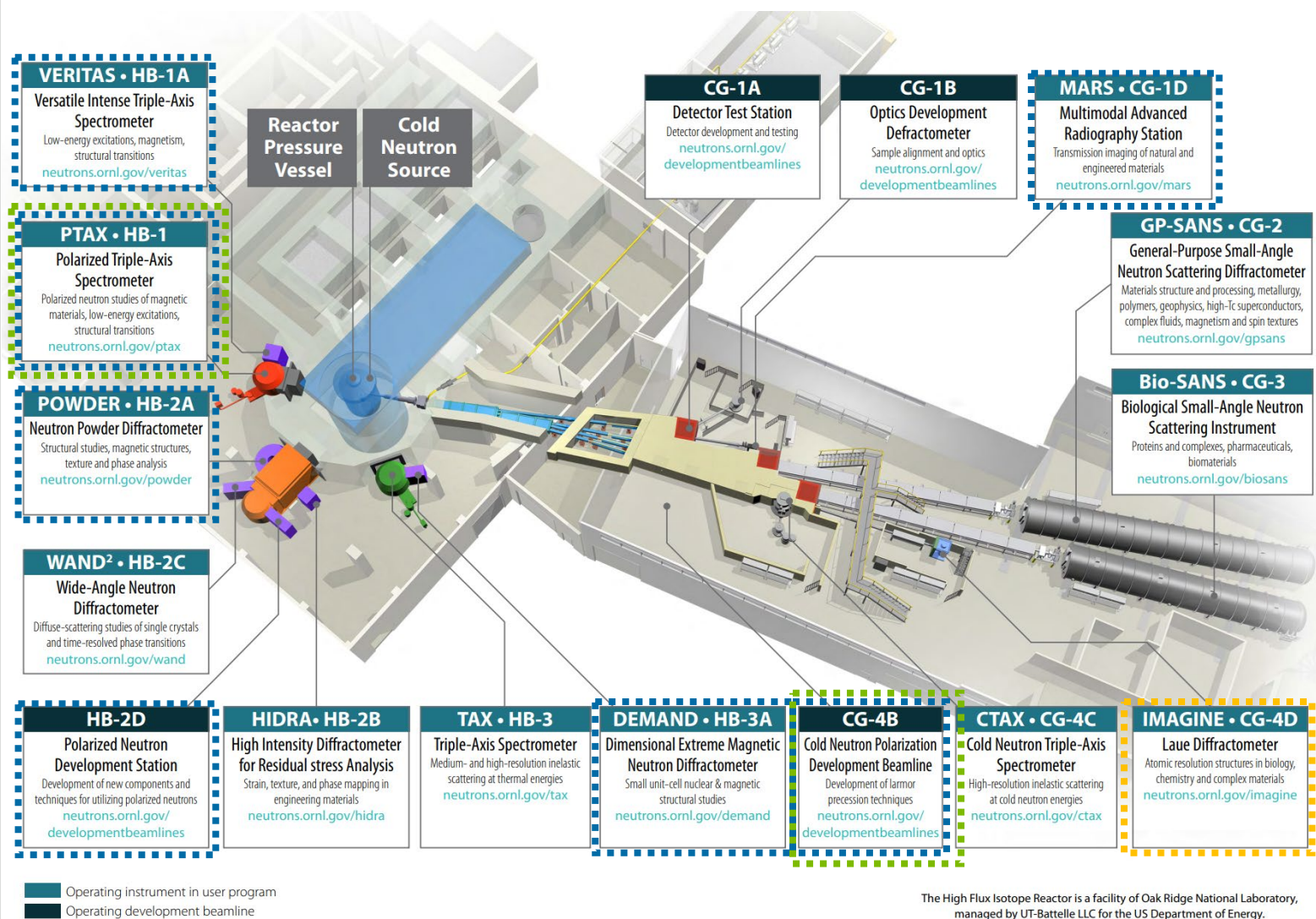
The Spallation Neutron Source is a facility of Oak Ridge National Laboratory, managed by UT-Battelle LLC for the US Department of Energy.

Who uses polarized neutrons at HFIR?

Magnetic Moment Contrast

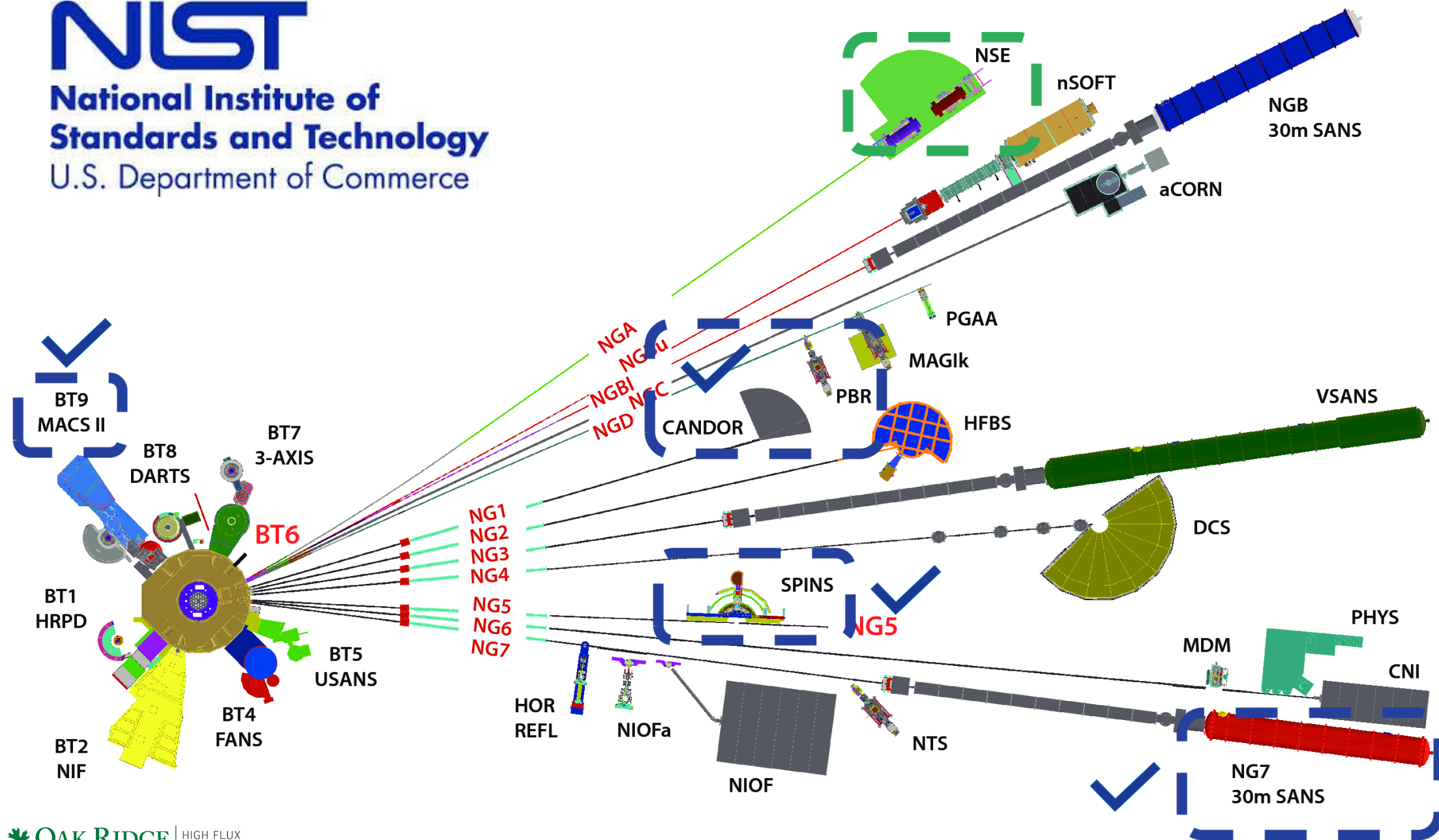
Nuclear Spin Contrast

Enhanced resolution via 'Larmor' techniques



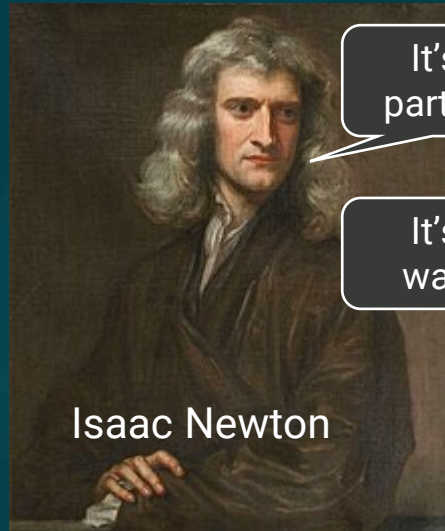
NIST

National Institute of
Standards and Technology
U.S. Department of Commerce



CHARACTER:

Neutrons sometimes behave as particles, and sometimes as waves



Isaac Newton

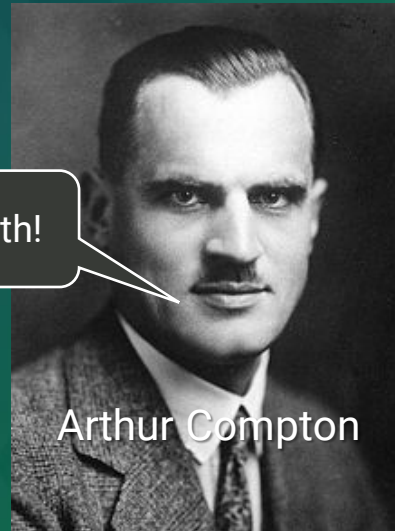
It's a particle!

It's a wave!



Christiaan Huygens

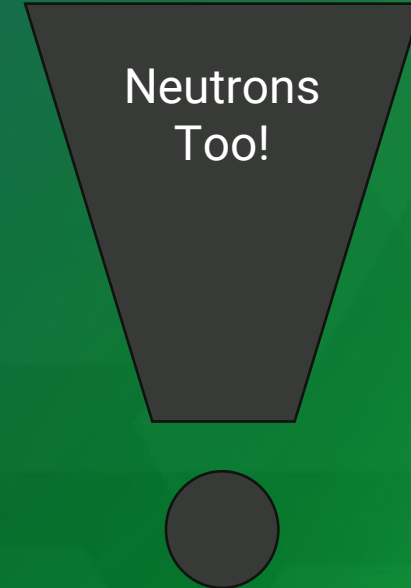
It's both!



Arthur Compton

Confusion about Light

"Solved" with
**Quantum
Mechanics**



Neutrons
Too!

CHARACTER:

Neutrons sometimes behave as particles, and sometimes as waves

Scatter like a wave



“Coherent” scattering

“Feels” more of a volume all at once,
Scattering VERY direction dependent

Examples of coherent scattering:

Diffraction (feels adjacent scatter planes)

Phonons (feels collective wiggles)

Index of refraction (feels density)

Scatter like a particle



“Incoherent” scattering

Single point of contact,
scatters in random directions

Loses ‘coherence’ via:

Random isotopes

Random nuclear spin orientations

Suppression of coherent scattering

CONTRAST: Neutrons scatter via 2 different forces, too

Nuclear Strong force



Interaction with nuclei of atoms
Depends on the *isotope*
Depends on *spin of the nuclei*
Depends on *nuclear resonances*

“Sees” lattice structure via nuclei location
“Sees” phonons & vibrational modes

Includes both scattering and **absorption**



(**absorption** is a nuclear reaction,
creating a new isotope
with an additional neutron)

Magnetic force



Interaction with the *magnetic field*
in a region about atoms

“Sees” magnetic structure
“Sees” magnetic excitations

Think
“Contrast” of
the scattering
neutron

CONTRAST: Neutrons scatter via 2 different forces, too

Nuclear
Strong force



Magnetic force



Real space: scatters off a point

Real space: scatters off extended volume, beyond even electron cloud

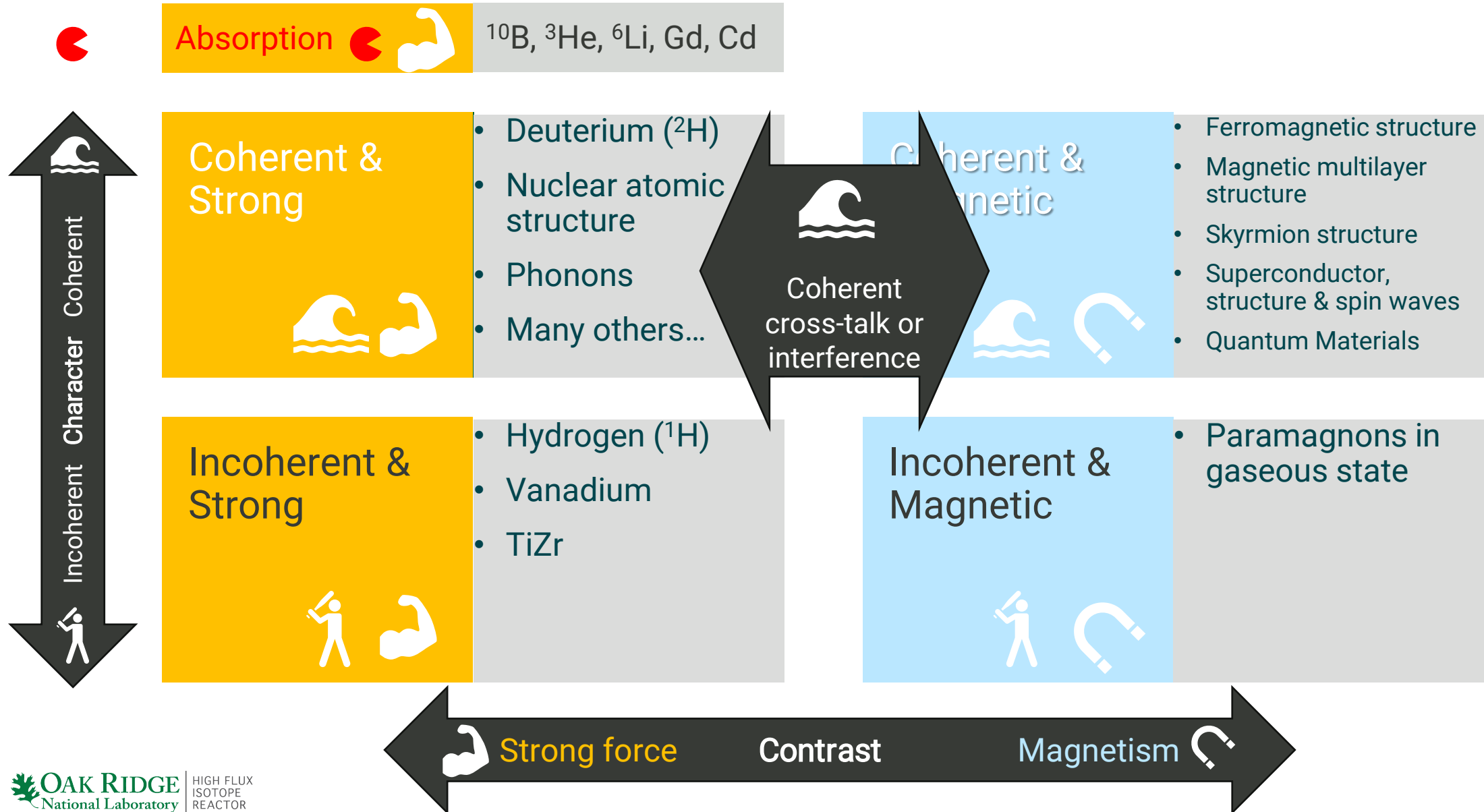
Reciprocal space: extends to high scatter angle / momentum transfer Q

Reciprocal space: strongest at low scatter angle / momentum transfer Q

Haiku for High Q :

*A neutron scatters
All over, nuclear strong
Not so, magnetic*

Combine Contrast & Character; or Particles, Waves & Forces



CONTRAST: Vector-ing from the perspective of the 2 forces

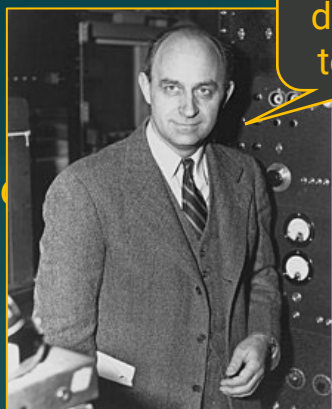
Strong force



Spin:
 $\sigma_n = \frac{1}{2}$

Quantum
weirdness

Fermions
don't like
to share



Enrico Fermi

Scattered intensity

Relative orientations of atomic nuclei

--- interacting with ---

--- leads to changes in ---

Magnetic force



Dipole moment:

$$\mu_n = -1.913 \mu_N$$

Nuclear magneton:

$$\mu_N = 5.051E-27 \text{ JT}^{-1}$$

$$\mu_N = 3.15E-5 \text{ meV/T}$$

Relative orientations



materials

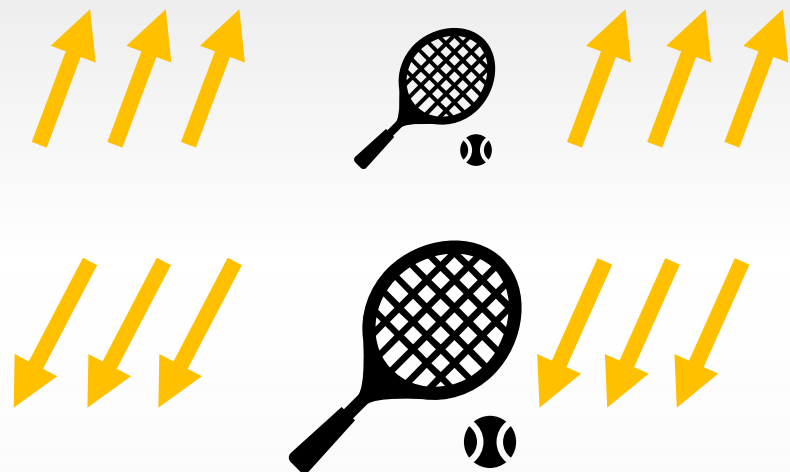
Reorientation of the

spin or magnetic moment of the neutron
3 charged quarks dancing inside each neutron

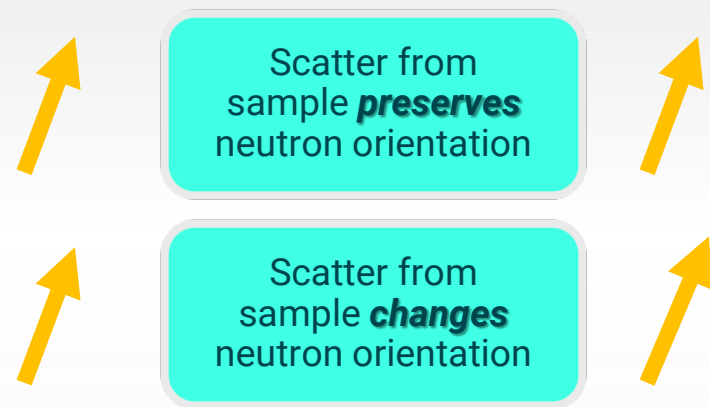


Changes depend on polarization of incident beam

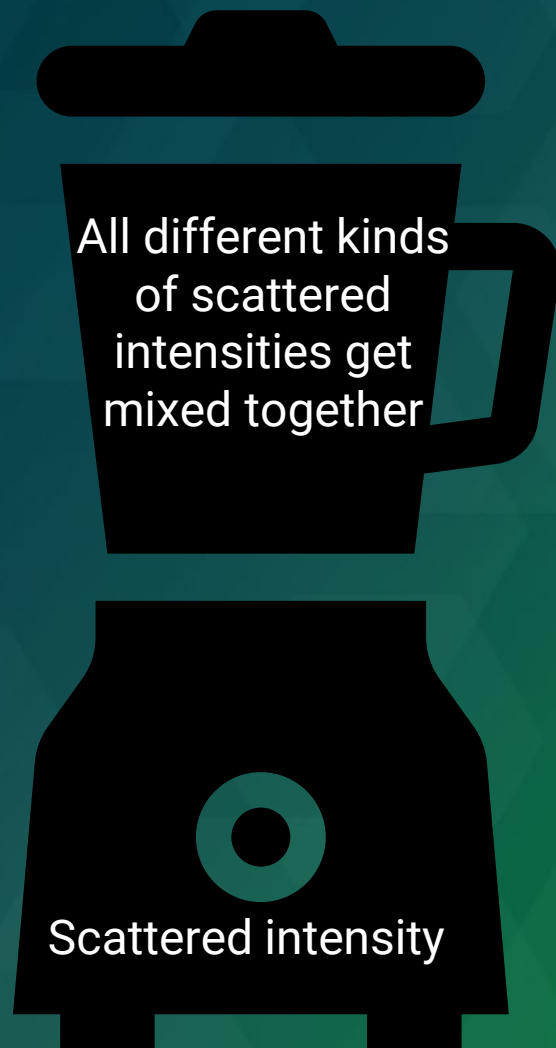
Changes in Scattered Neutron Intensity



Changes in Neutron Orientation



Yet, with unpolarized neutron scattering alone...



sp

of the neutron

ent

If only we had a way to filter and play with

the neutron **spin** or magnetic moment...





We could isolate different features



We could reveal different dimensions



We could answer new questions
(that we'll call 'CAPABILITIES')



But beware, 'polarization' has 4 meanings for neutron scattering

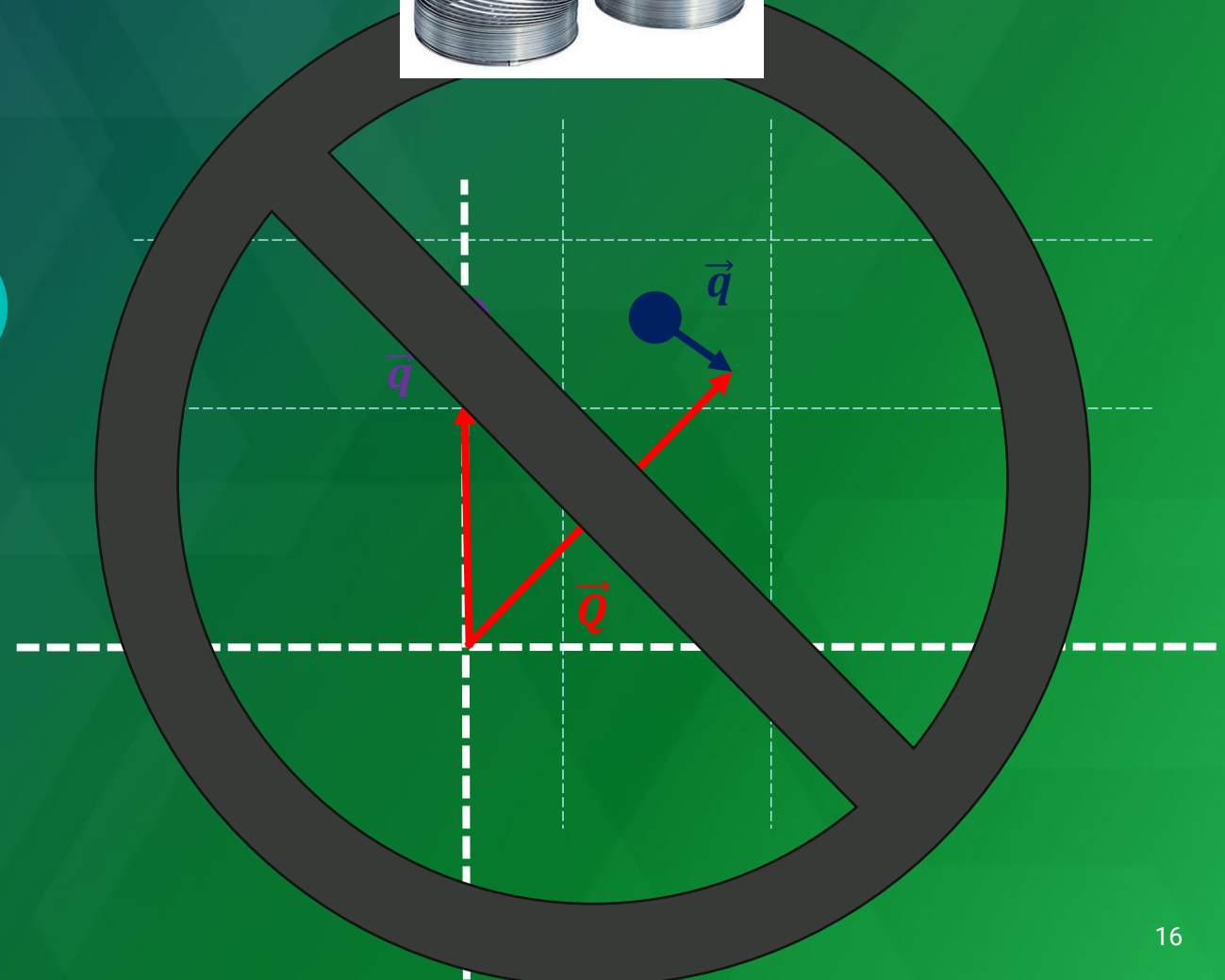
1



2

$$-1 \geq P \geq 1$$

3



What? ANOTHER meaning for polarization?

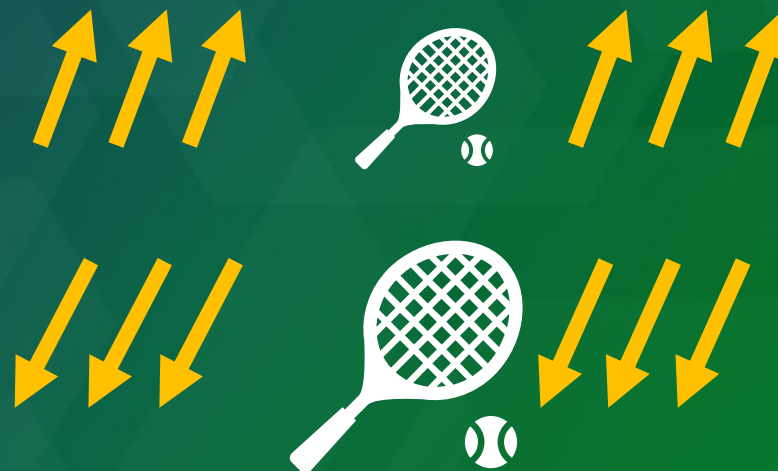
4

This time, we're NOT referring to polarization of the neutron
INSTEAD, we're co-aligning either ATOMIC NUCLEI spins or
magnetic moments inside of some material

In this case, the MATERIAL is 'polarized' instead of the neutron!



Polarized materials can change scattered intensity of polarized neutrons





Ingredients for CONFIGURATIONS: Polarization Optics

Guide fields, Flippers, and Filters

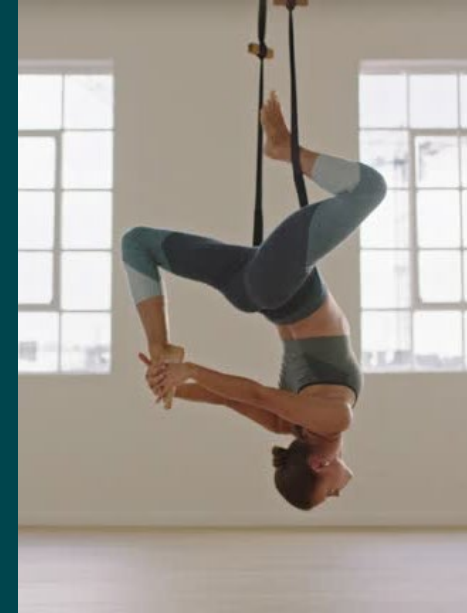
Guide fields & Larmor precession



Ice skater



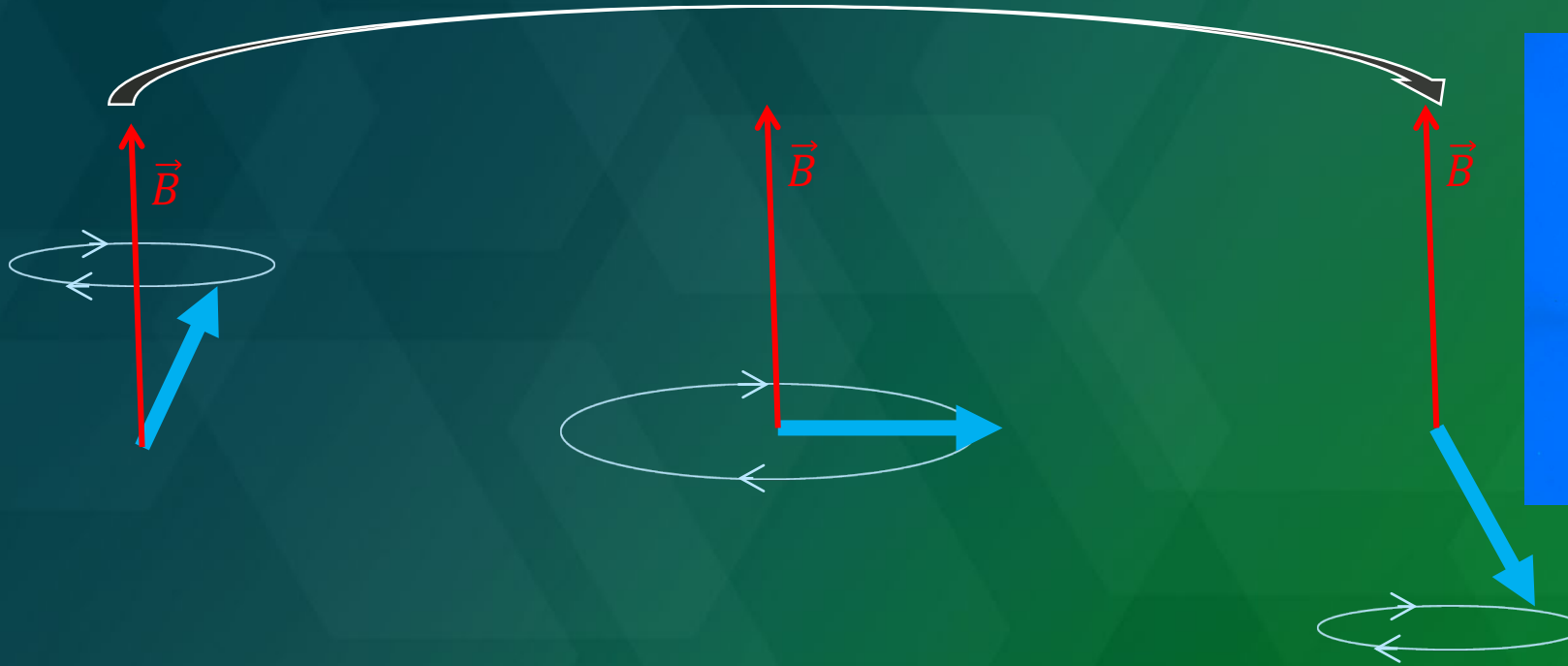
Break dancer



Rope dancer

Guide fields & Larmor precession

$$\vec{\omega} = k\vec{B}$$



(mostly) parallel

$P \sim 1$

Right angle

$P \sim 0$

(mostly) antiparallel

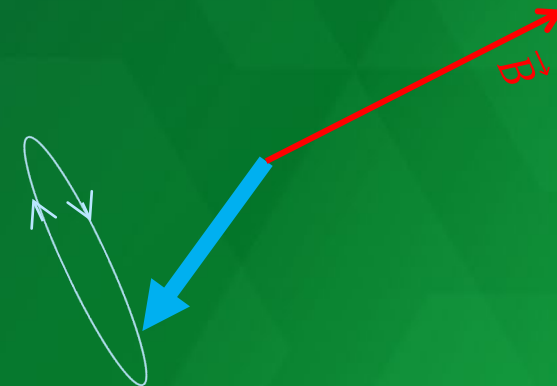
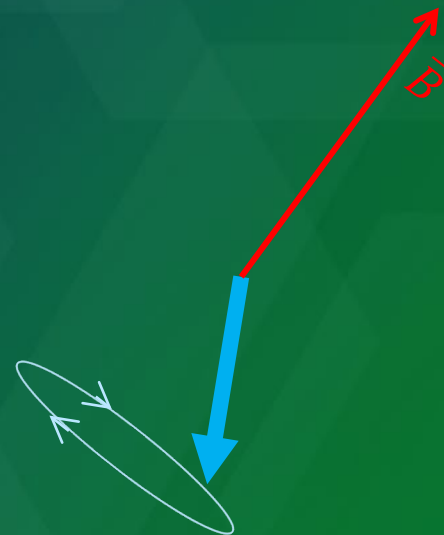
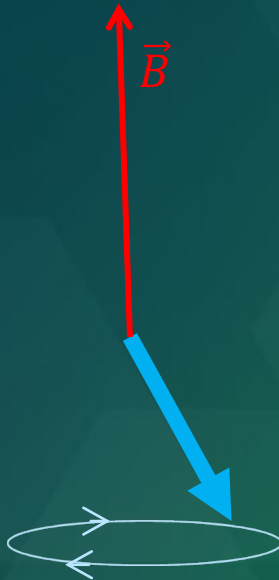
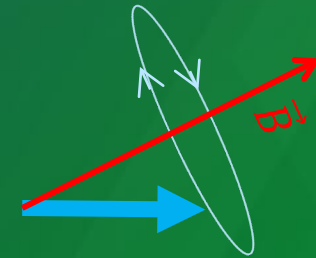
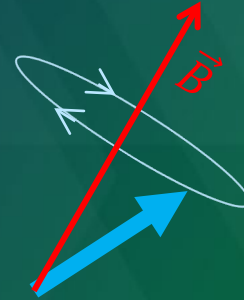
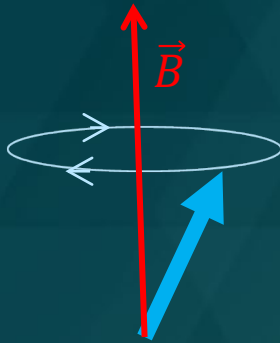
$P \sim -1$



Guide fields as 'nutators'

Steering neutron moment while flying is possible

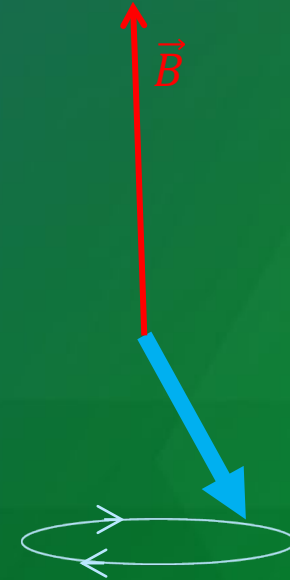
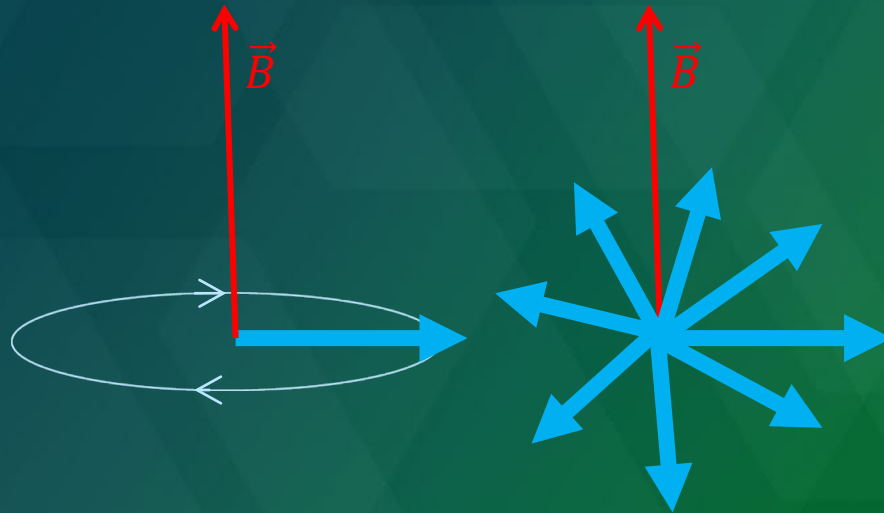
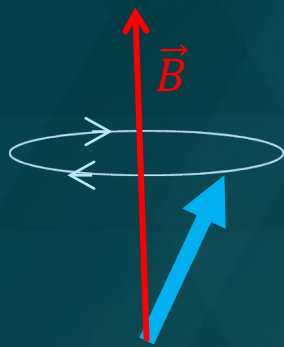
-IF- we precess fast enough to track the change in field direction



A Quantum perspective for Larmor Precession helps to figure how FILTERS work



Classical



Quantum



So, if we could FILTER while the neutron is experiencing an external magnetic field, we could pass through up to half the neutrons!?!

Taking changes in scattered intensity to the EXTREME: From 'unpolarized' random directions in a neutron beam to HALF having single direction

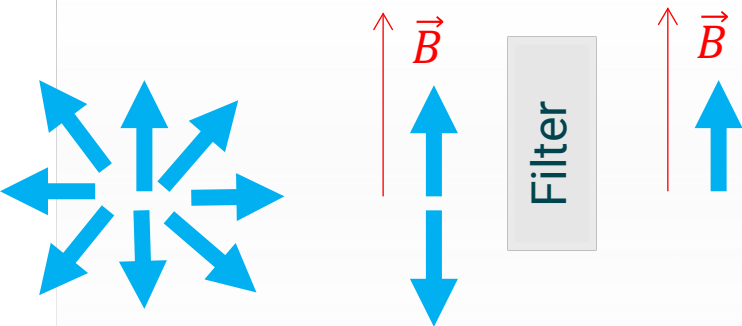
Polarized neutron developers have, over time, found and developed awesome materials that scatter or absorb selectively just one neutron state

These EXTREME systems are now optics we use as polarization FILTERS



Filters

- 'Quantum' has its advantages...
 - Unpolarized classical has arrows pointing everywhere
 - In ambient field, though, a quantum superposition of 'up' & 'down'
 - A filter can achieve up to* 50% transmission



*Actual transmission varies widely...

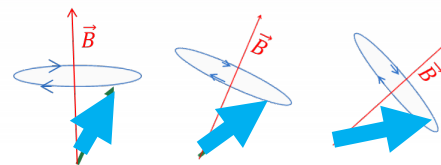
Guide fields and nutators

- Larmor precession, via torque $\vec{\tau}$ on neutron magnetic moment $\vec{\mu}$ by applied magnetic field $\vec{B}$

$$\vec{\tau} = \vec{\mu} \times \vec{B}, \omega = -\gamma B$$

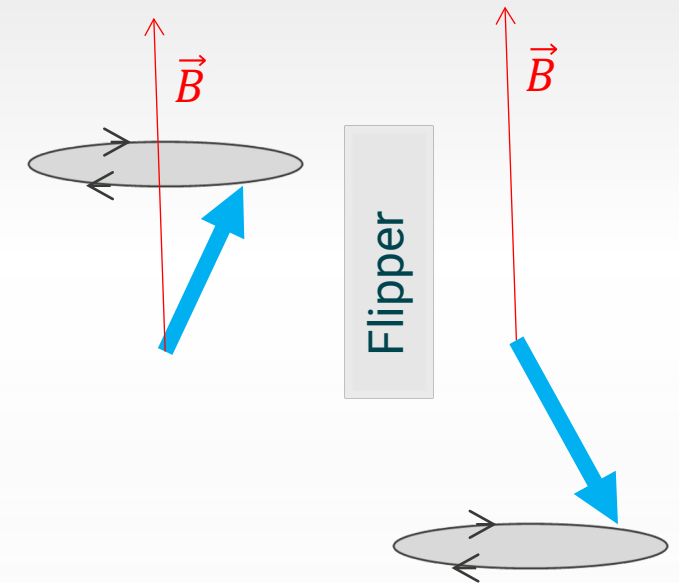
$$\gamma = -1.833\text{E}4 \text{ rad/Gauss-sec}$$

- Frequency ω is INDEPENDENT of polar angle φ between applied field and moment
- Magnetic 'guide' fields keep $\vec{\mu}$ either aligned or anti-aligned with respect to $\vec{B}$
 - Keeps ω fast while changing direction of $\vec{B}$ slowly



Flippers

- Optionally invert the neutron spin-state with respect to the ambient guide field



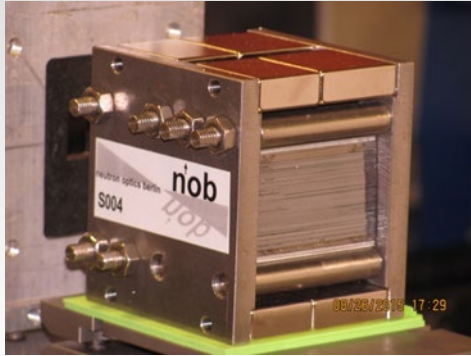
Polarization optics

Filters

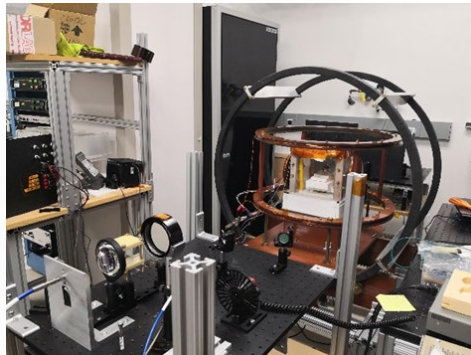
Heusler crystal



Polarizing Supermirror

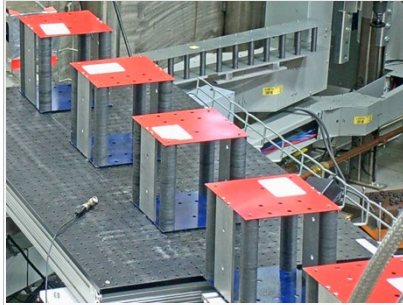


Nuclear-polarized ^3He

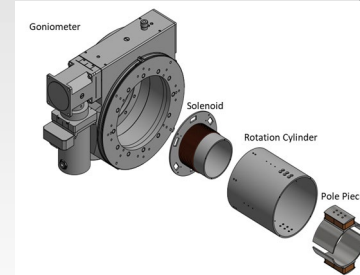


Guide fields and nutators

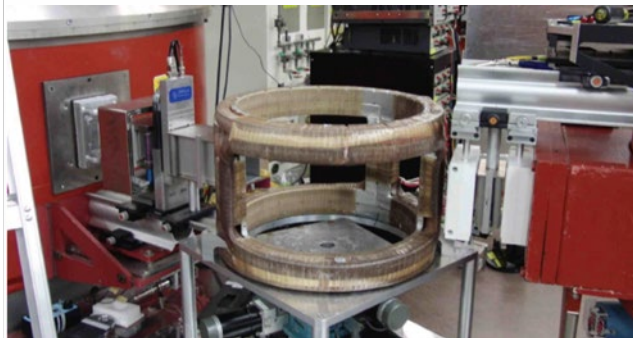
Permanent Magnet
Yoked Assemblies



Rotatable nutator



3D Coils



Flippers

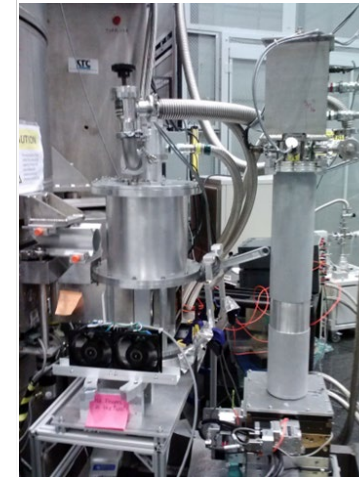
Mezei



Radio-Frequency



Cryogenic
(Meissner screen)



Adiabatic Fast
Passage /w ^3He





Scattering changes accessed by different CONFIGURATIONS

Ways to measure changes in scattered intensity and/or changes in neutron polarization orientation



Add changes to scattered intensity to the Contrast / Character Matrix

Absorption



^3He filters absorb just 1 spin state*



Coherent & Strong



Dynamic Nuclear Polarization

- When 'polarize⁴' the ^1H nuclei
- IMAGINE-X

Coherent & Magnetic



When 'polarizing⁴' your sample

- Ferromagnets
- Ferrimagnets
- Paramagnets
- Constructive / deconstructive interference for specific Bragg peaks: e.g. Heusler crystals

Magnetic chiral structures

Coherent cross-talk or interference

Incoherent & Strong



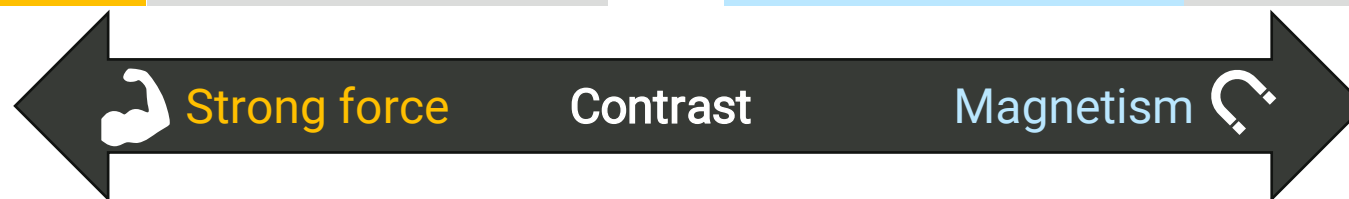
Scatters only one spin state for ^1H

- Naphtaline as polarization filter for unscattered beam*

Incoherent & Magnetic

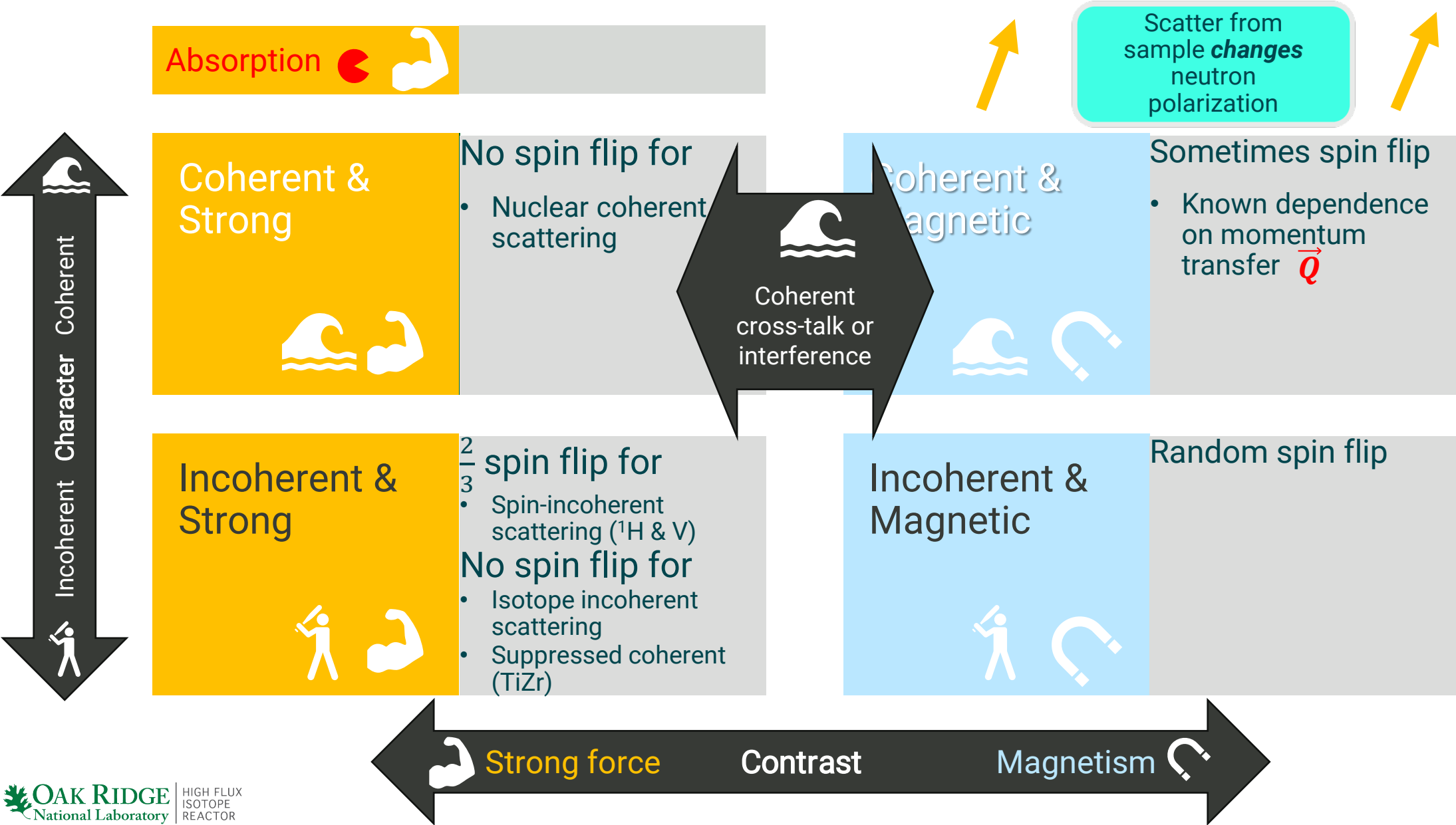


No change





Add Vector Reorientation to the Contrast / Character Matrix



Formulas on next page leverage lattice periodicity & coherent scattering

Coherence mechanism #1:
Leverage ***lattice periodicity*** for single crystals or powders
(think Bragg's law, Bloch equations, etc.)

Useful for ***diffraction*** and ***coherent inelastic scattering*** in comparable Q ranges

Leads to 'Maleev-Blume' equations with '***simple***' formulas relating various contributions to scattering ***into*** changes in neutron scattering intensity and/or polarization state

Will utilize Maleev-Blume vector equations as instructional aid for this introduction

Coherence mechanism #2:
Leverage # ***density variations*** leading into optical density variations

Useful for ***small angle neutron scattering (SANS)*** and ***reflectometry***

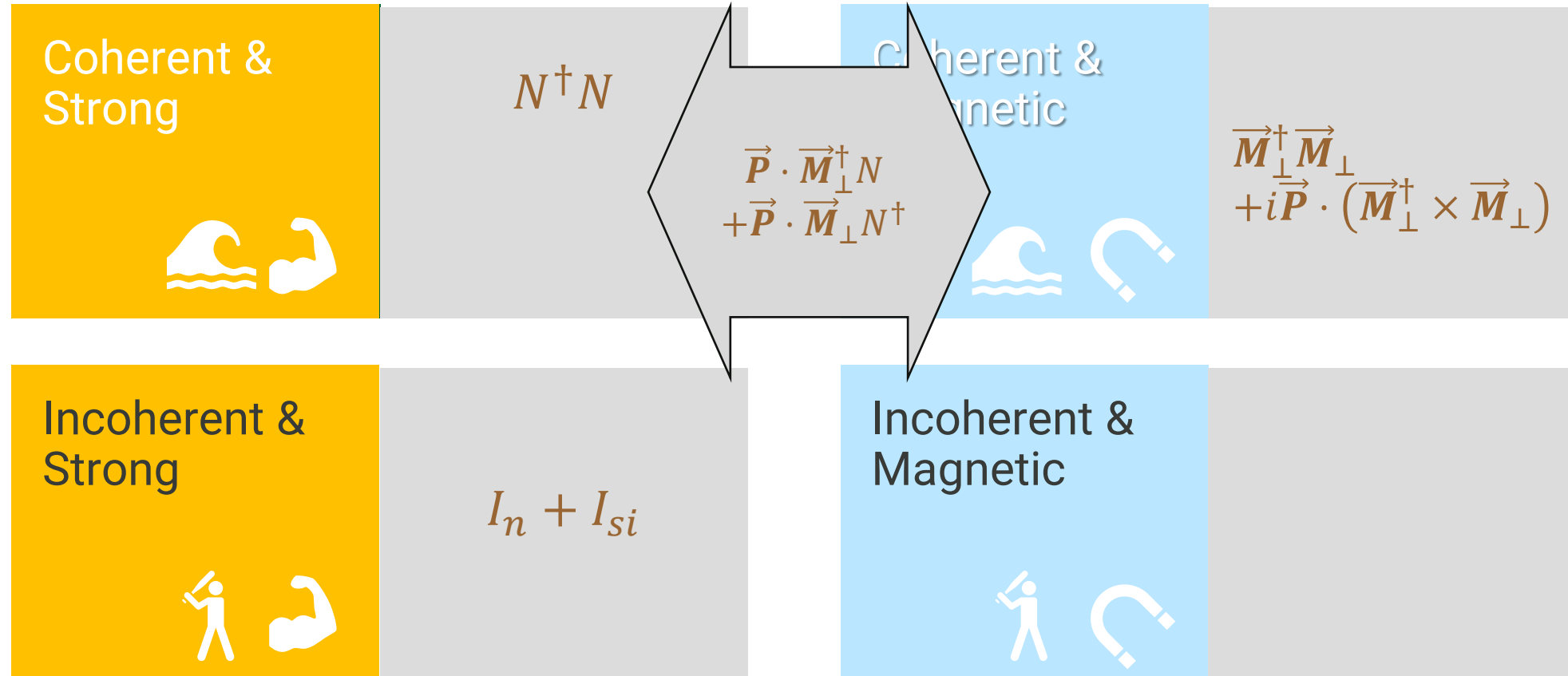
For e.g. 1D multilayer systems, NOT periodic so must ***directly solve Schrodinger's equation***

Similar approach to coherent interference effects
(here often called 'contrast matching')



Add *changes to scattered intensity* to the Contrast / Character Matrix

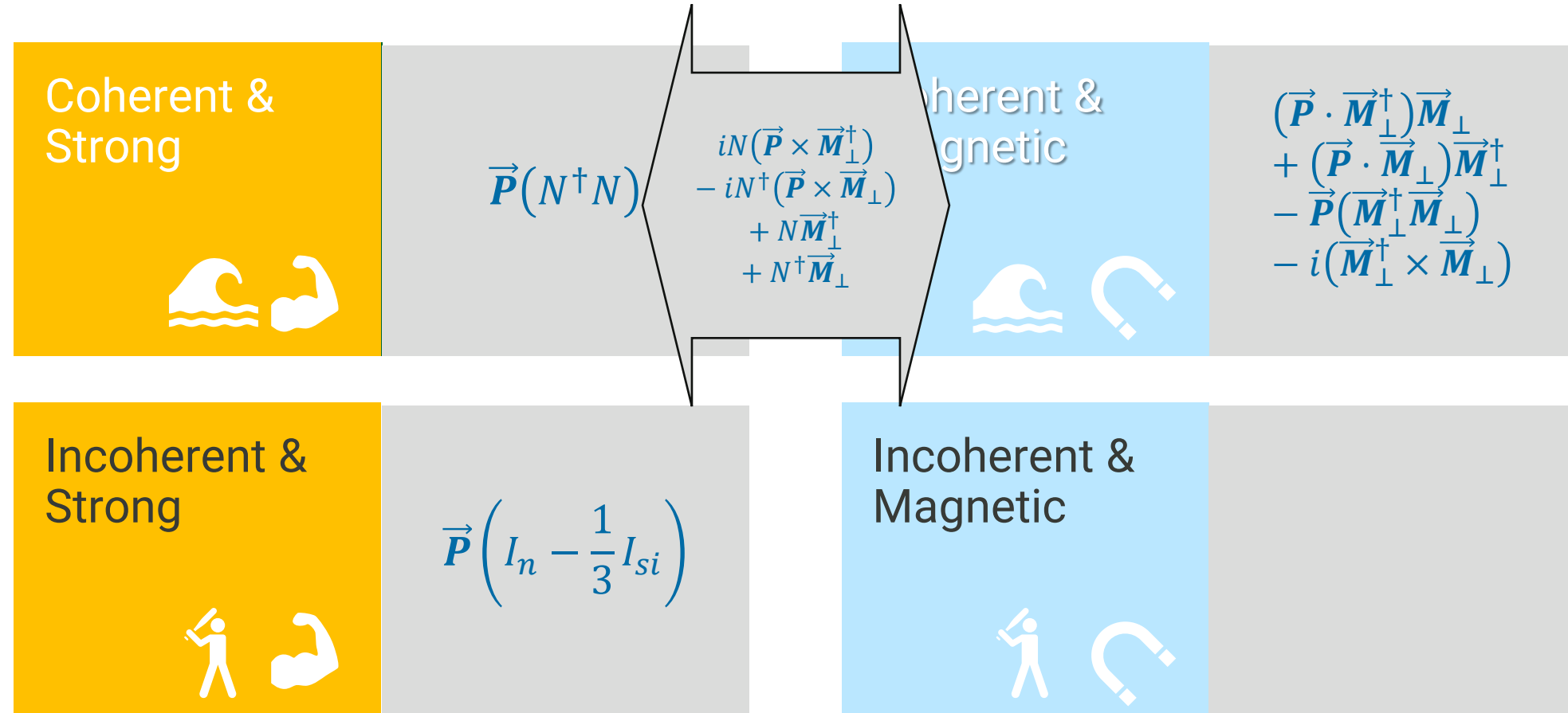
$$I = I_n + N^\dagger N + I_{si} + \vec{M}_\perp^\dagger \vec{M}_\perp + \vec{P} \cdot \vec{M}_\perp^\dagger N + \vec{P} \cdot \vec{M}_\perp N^\dagger + i\vec{P} \cdot (\vec{M}_\perp^\dagger \times \vec{M}_\perp)$$





Add Vector Reorientation to the Contrast / Character Matrix

$$\mathbf{P}^{\dagger}I = \mathbf{P} \left(I_n + N^{\dagger}N - \frac{1}{3}I_{si} \right) + (\mathbf{P} \cdot \mathbf{M}_{\perp}^{\dagger})\mathbf{M}_{\perp} + (\mathbf{P} \cdot \mathbf{M}_{\perp})\mathbf{M}_{\perp}^{\dagger} - \mathbf{P}(\mathbf{M}_{\perp}^{\dagger}\mathbf{M}_{\perp}) + iN(\mathbf{P} \times \mathbf{M}_{\perp}^{\dagger}) - iN^{\dagger}(\mathbf{P} \times \mathbf{M}_{\perp}) + N\mathbf{M}_{\perp}^{\dagger} + N^{\dagger}\mathbf{M}_{\perp} - i(\mathbf{M}_{\perp}^{\dagger} \times \mathbf{M}_{\perp})$$



Meet the “Vector” family

$\vec{R}_n$		Coordinates of one atom in unit cell for crystal	Real space
$\vec{M}_n$		Which way and how strong a magnetic moment of an <i>ATOM</i> points	
$\vec{P}$	Polarization	A measure of how ‘polarized’ the incident beam is, and average orientation of those neutrons’ spin (or magnetic moment) at sample position (definition #2)	
$\vec{P}^1$		The new polarization of the scattered neutrons	
$\vec{Q}$	Momentum transfer	Incident neutron momentum minus final neutron momentum $\vec{Q}_{lab} = \vec{k}_i - \vec{k}_f$	Reciprocal space
$\vec{M}(\vec{Q})$	Magnetic structure factor	Fourier transform of $\vec{M}_n$	
$\vec{M}_\perp$	“M perp”	The component of the Magnetic structure factor perpendicular to the momentum transfer $\vec{Q}$	

Polarization CONFIGURATIONS access Intensity and/or Polarization State

$N(\mathbf{Q}) = \sum_n b_n e^{i\mathbf{Q} \cdot \mathbf{R}_n}$	Nuclear structure factor
$\mathbf{M}_\perp = \mathbf{e}_Q \times \mathbf{M}(\mathbf{Q}) \times \mathbf{e}_Q$	"M perpendicular"
$\mathbf{M}(\mathbf{Q}) = \sum_n \mathbf{M}_n e^{i\mathbf{Q} \cdot \mathbf{R}_n}$	Fourier transform of magnetic moments / magnetic structure factor
$\mathbf{e}_Q = \mathbf{Q}/ \mathbf{Q} $	Unit vector along momentum transfer $\mathbf{Q}$
I_{si}	Spin incoherent scattered intensity
$\mathbf{P}, \mathbf{P}^\dagger$	Initial and final polarization

POLARIZATION CONFIGURATION	Impacts the scattered neutron	Optics
Half Polarized Dynamic Nuclear Polarization Solve Phase Problem	Intensity	1 filter 1 flipper
Longitudinal Analysis I Larmor	Polarization State	2 filters 1 flipper
Longitudinal Analysis II Spherical Neutron Polarimetry	Both	2 filters 2 flippers

Changes in scattered intensity

$$I = I_n + N^\dagger N + I_{si} + \mathbf{M}_\perp^\dagger \mathbf{M}_\perp + \mathbf{P} \cdot \mathbf{M}_\perp^\dagger N + \mathbf{P} \cdot \mathbf{M}_\perp N^\dagger + i\mathbf{P} \cdot (\mathbf{M}_\perp^\dagger \times \mathbf{M}_\perp)$$

Changes in neutron orientation

$$\mathbf{P}^\dagger I = \mathbf{P} \left(I_n + N^\dagger N - \frac{1}{3} I_{si} \right) + (\mathbf{P} \cdot \mathbf{M}_\perp^\dagger) \mathbf{M}_\perp + (\mathbf{P} \cdot \mathbf{M}_\perp) \mathbf{M}_\perp^\dagger - \mathbf{P} (\mathbf{M}_\perp^\dagger \mathbf{M}_\perp) + iN (\mathbf{P} \times \mathbf{M}_\perp^\dagger) - iN^\dagger (\mathbf{P} \times \mathbf{M}_\perp) + N \mathbf{M}_\perp^\dagger + N^\dagger \mathbf{M}_\perp - i(\mathbf{M}_\perp^\dagger \times \mathbf{M}_\perp)$$

¹S. V. Maleev, V. G. Bar'yaktar, and R. A. Suris, The scattering of slow neutrons by complex magnetic structures Sov. Phys. Solid State 4, 2533 (1963)

²M. Blume, Polarization effects in the magnetic elastic scattering of slow neutrons, Phys. Rev. 130, 1670 (1963).

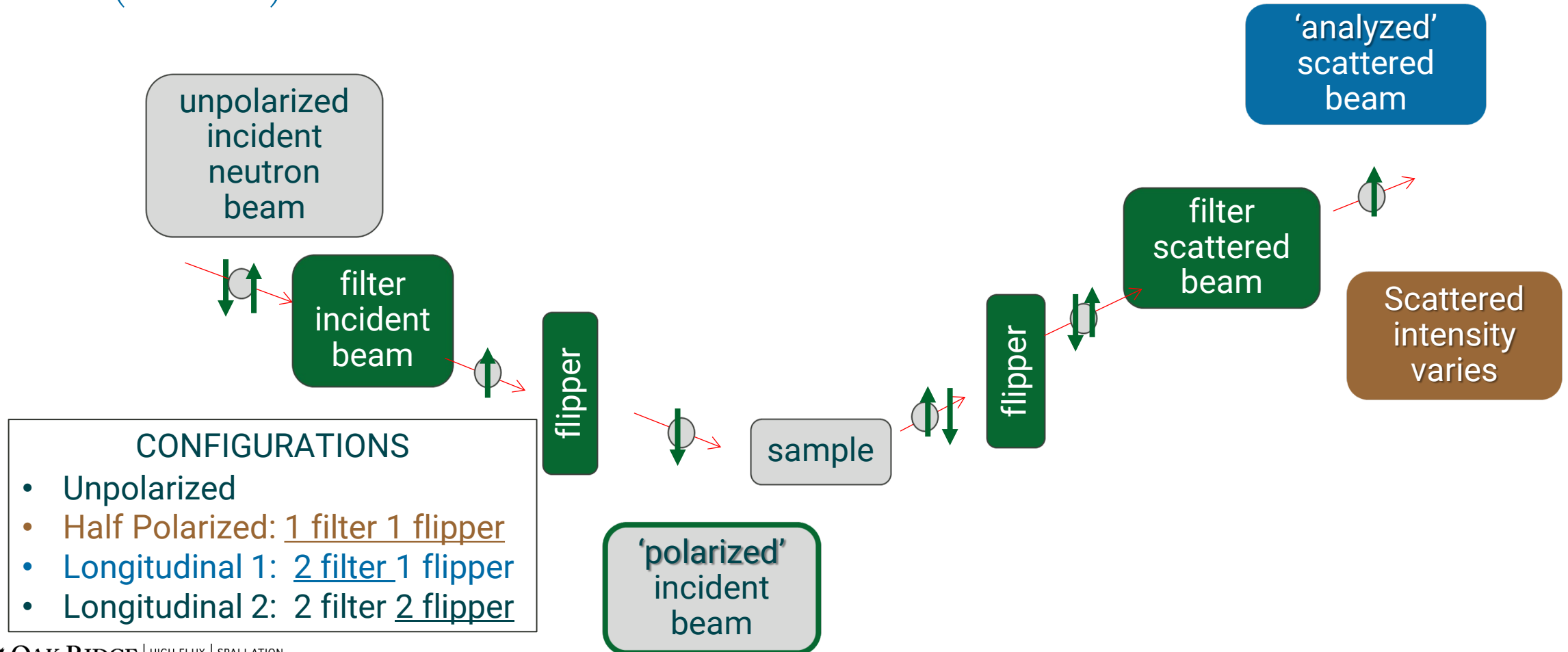
CONFIGURATIONS, what they access, and their optics

Changes in scattered intensity

$$I = N^\dagger N + I_{si} + \mathbf{M}_\perp^\dagger \mathbf{M}_\perp + \mathbf{P} \cdot \mathbf{M}_\perp^\dagger N + \mathbf{P} \cdot \mathbf{M}_\perp N^\dagger + i\mathbf{P} \cdot (\mathbf{M}_\perp^\dagger \times \mathbf{M}_\perp)$$

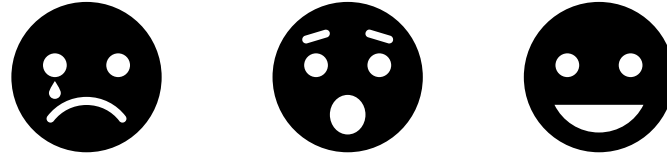
Changes in neutron orientation

$$\mathbf{P}^\dagger I = \mathbf{P} \left(N^\dagger N - \frac{1}{3} I_{si} \right) + (\mathbf{P} \cdot \mathbf{M}_\perp^\dagger) \mathbf{M}_\perp + (\mathbf{P} \cdot \mathbf{M}_\perp) \mathbf{M}_\perp^\dagger - \mathbf{P} (\mathbf{M}_\perp^\dagger \mathbf{M}_\perp) + iN (\mathbf{P} \times \mathbf{M}_\perp^\dagger) - iN^\dagger (\mathbf{P} \times \mathbf{M}_\perp) + N \mathbf{M}_\perp^\dagger + N^\dagger \mathbf{M}_\perp - i(\mathbf{M}_\perp^\dagger \times \mathbf{M}_\perp)$$



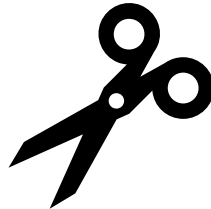
CAPABILITIES truncate those equations

Yes, the Maleev-Blume equations are VERY busy



- Leverage *personality flaw* found in some scientists

- A. *Make assumptions* about the system you are studying
- B. Eliminate terms
- C. Simplify / Streamline the math



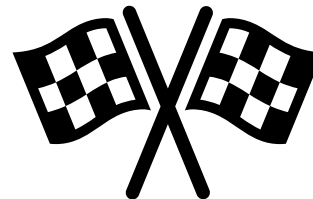
- Linear algebra

- N equations & N unknowns $\rightarrow$ solvable problem



- Let's call the solutions to the streamlined equations
"Capabilities"

- Think word problems in reverse...



CONFIGURATIONS, CAPABILITIES and Capability Families

- “Configurations” are specific combinations of polarization optics enabling access to different Maleev-Blume equations
 - Will show examples of configurations in upcoming slides!
- “Capabilities” are specific solutions to streamlined Linear algebra problems
 - Can only be solved utilizing a subset of “Configurations”
 - Assume certain terms in Maleev-Blume equations aren’t present
 - Polarization-state ‘equation’ is actually several equations
- “Capability families” are intuitive (?) groupings of those specific solutions

Capability Families

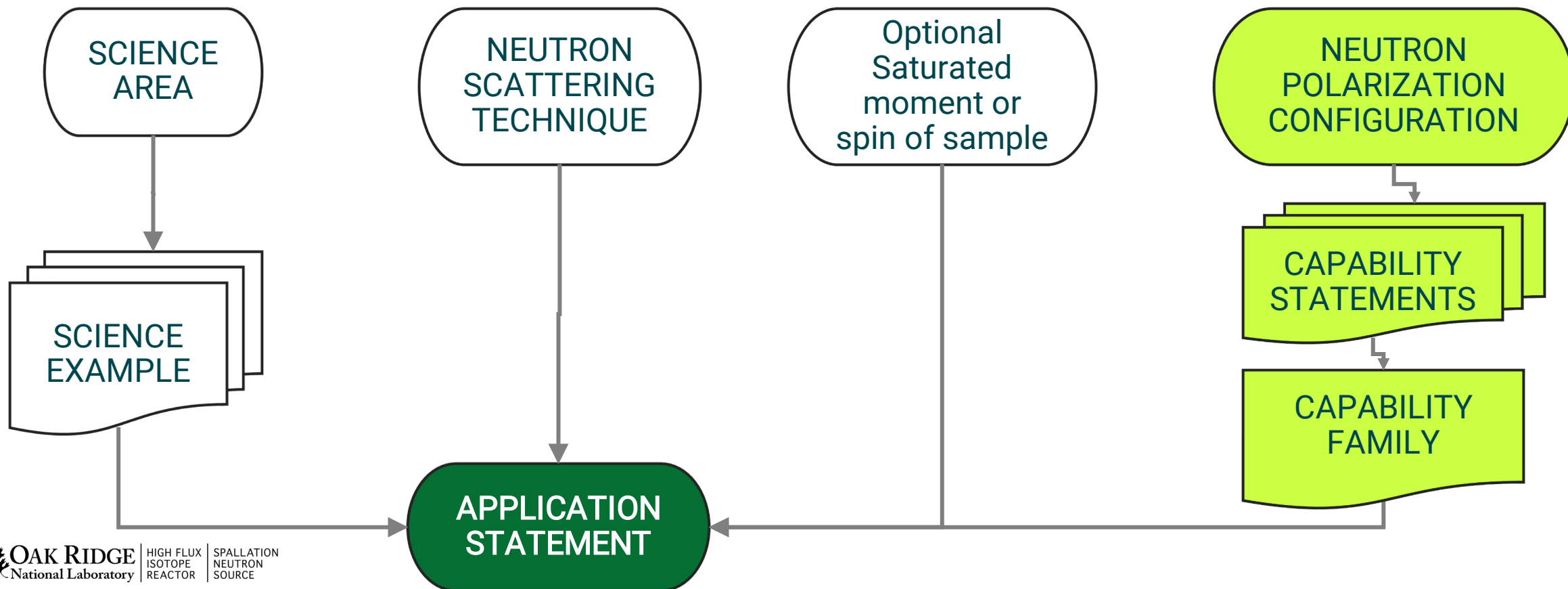
Isolate nuclear scattering	$N \& I_N$
Isolate spin-incoherent scattering	I_{si}
Leverage dynamic nuclear polarization	$N \leftrightarrow I_{si}$
Solve Phase Problem	$N \& \mathbf{M}_{\perp}$
Explore magnetic scattering	$\mathbf{M}_{\perp}$
Explore coinciding of nuclear and magnetic scattering	$N \text{ with } \mathbf{M}_{\perp}$
Explore magnetic chirality	$\mathbf{M}_{\perp}$ cross terms

Color Key

Nuclear Scattering (coherent & isotope-incoherent)
Spin-Incoherent Scattering
Magnetic Scattering
Dynamic Nuclear Polarization
Other

Ingredients for your 'polarized' application statement

As a [**SCIENCE AREA**] neutron scattering experimentalist, I want to
 [**NEUTRON SCATTERING TECHNIQUE**]
 so I can [**APPLICATION statement**] for [**SCIENCE EXAMPLE**]





Active development and community

- Semi annual meetings / proceedings of PNCMI (Polarized Neutrons for Condensed Matter Investigations)
 - Proceedings from 2016:
<https://iopscience.iop.org/issue/1742-6596/862/1>
 - Proceedings from 2018:
<https://iopscience.iop.org/issue/1742-6596/1316/1>
 - Proceedings from 2022:
<https://iopscience.iop.org/issue/1742-6596/2481/1>
- Aspirations & new directions at ORNL & NCNR
 - Just ask!
- Actively building user community via training workshops

For future reading

- Several dissertations
 - See instrument-specific publication lists
- Workshop slides, Polarization for Quantum Materials
 - Ovi, Masa, Yiqing & me, every other year
- Various online slide decks and tutorials
 - Kathryn Krycka, 'Neutron Polarization' slides & video at <https://neutrons.ornl.gov/nxs/2021/lectures>
 - Werner Schweika, https://user.fz-juelich.de/record/20415/files/C6_Schweika.pdf
- Books / chapters
 - Tapan Chatterji (ed.), *Neutron Scattering from Magnetic Materials* (2006) / several chapters
 - Stephen W Lovesey, *Theory of Neutron Scattering from Condensed Matter V2* (1984) / ch 10
 - G. Shirane, SM Shapiro, JM Tranquada, *Neutron Scattering with a Triple Axis Spectrometer* (2002) / ch 8