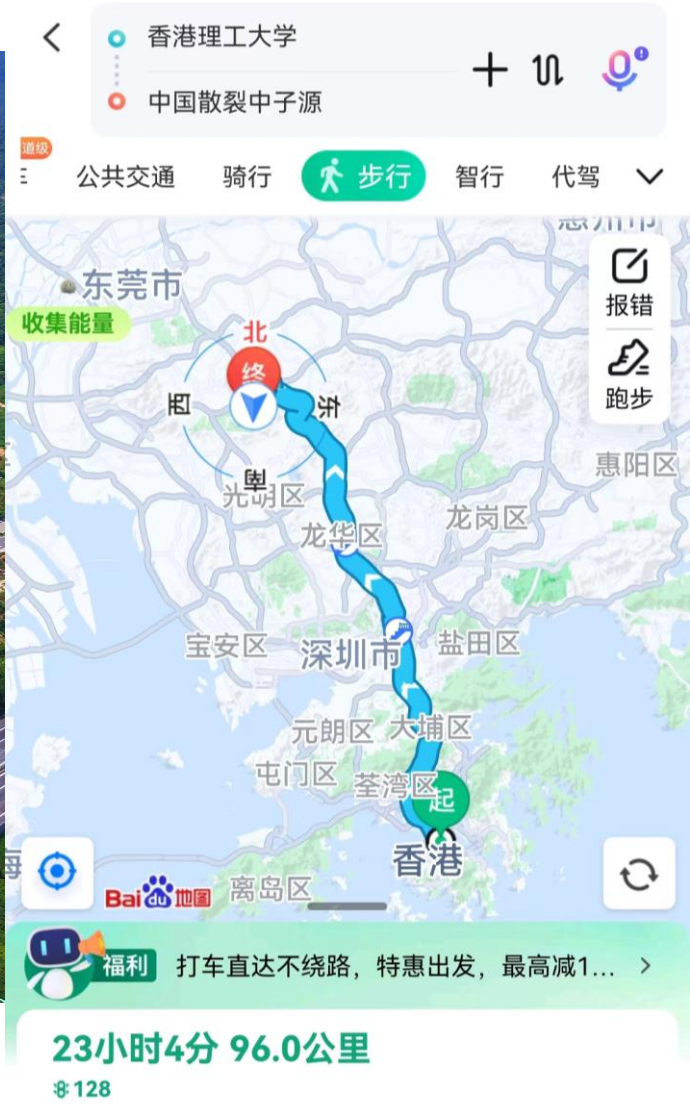
Neutron Scattering
-a very brief introduction

Xin Tong

China Spallation Neutron Source
Institute of High Energy Physics

Location of the CSNS





Outlines

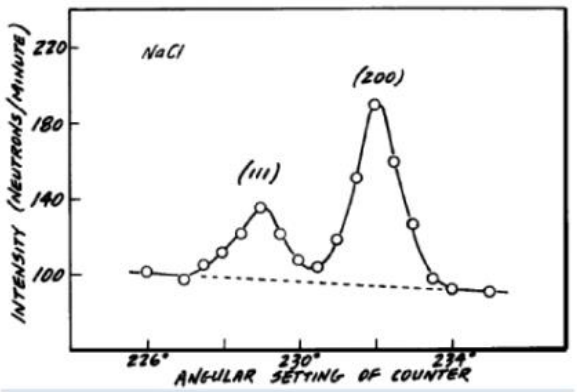
1. Brief history of neutron and neutron scattering
2. Basic theory of neutron scattering
3. X-ray scattering vs. neutron scattering
4. Neutron production and neutron facilities
5. Moderation
6. Neutron instrumentation, neutron optics
7. Sample requirement and sample environment
8. Neutron detection
9. Polarized neutrons
10. Typical examples
11. Exotic neutron experiments (if I have time for it)
12. More Exotic neutron experiments (if I have time for it)

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1. Brief history of neutron and neutron scattering
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Some Neutron Scattering History

- 1932 – Chadwick discovers the neutron
- 1934 – thermalisation (Fermi)
- 1936 – scattering theory (Breit, Wigner)
- 1936 – wave interference (Mitchell, Powers)
- 1939 – fission

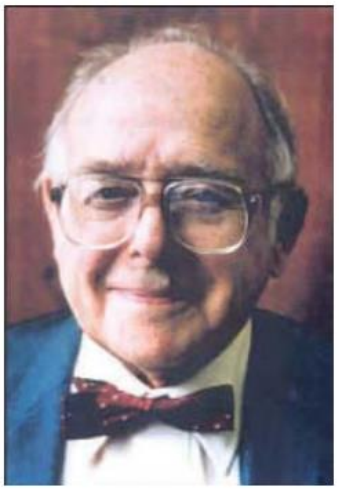


- 1945 – diffraction (Shull, Wollan), reflection, refraction
- 1948 – coherent & incoherent scattering (Shull, Wollan)
- 1948 – spallation
- 1949 – structure of AFM (Shull)

- 1951 – polarized neutrons (Shull & Wollan)
- 1955 – three axis spectrometer (Brockhouse)
- 1958 – rotons in helium (Palevsky, Otnes, Larsson)

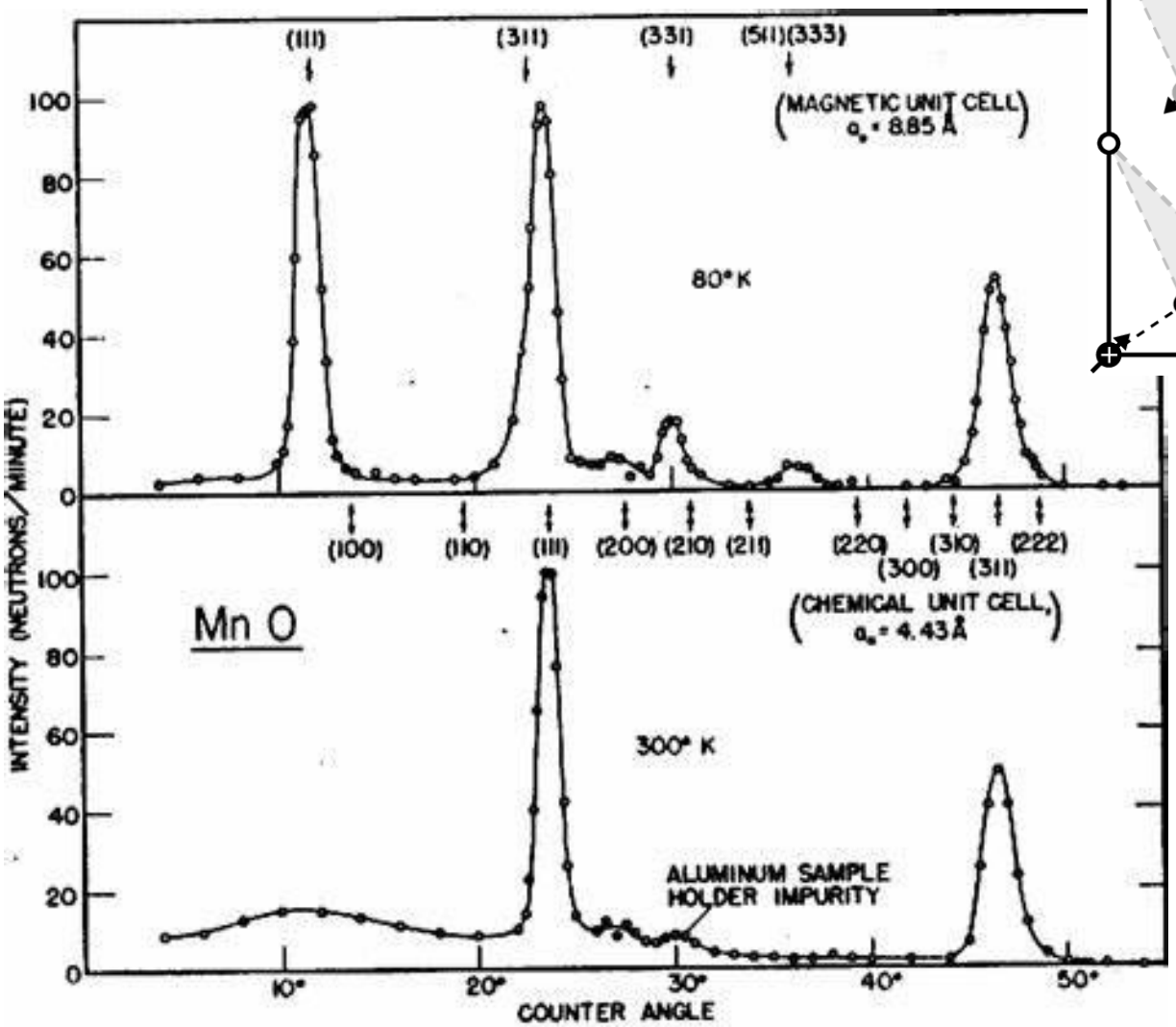
- 1962 – Kohn anomalies
- 1960 – 79 – soft phonons & structural phase transitions
- 1969 – 79 – scaling and universality

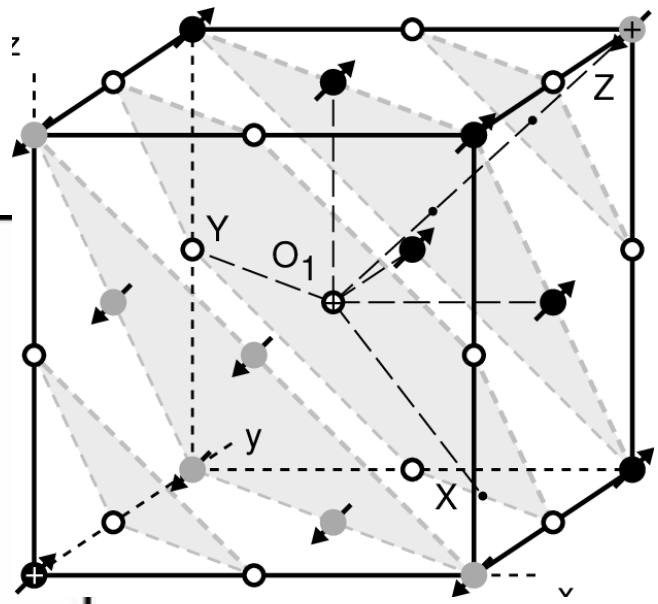
- 1972 – conformation of polymers
-
- 1994 – Nobel Prize for Shull and Brockhouse



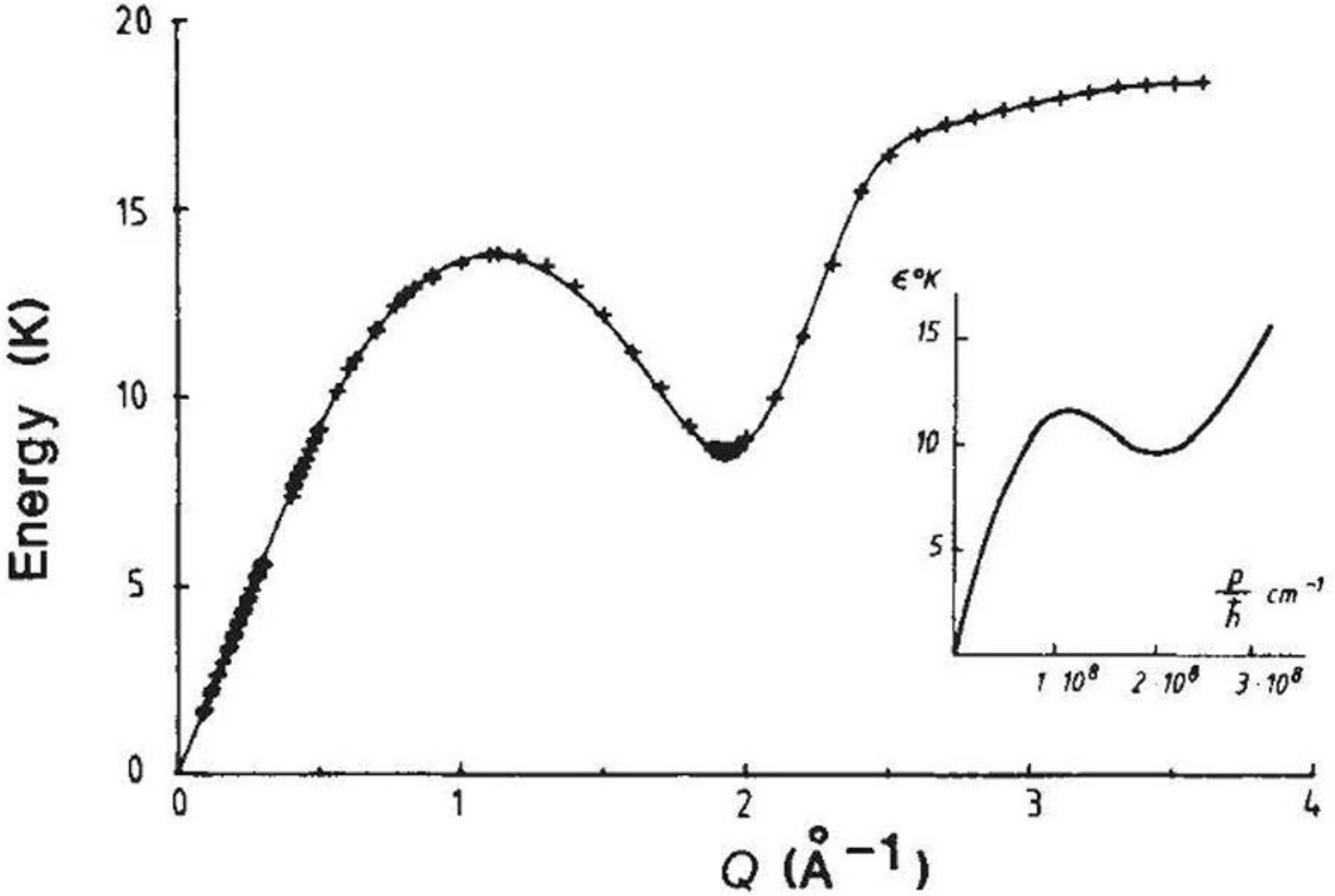
Cliff Shull (1915 – 2001)

One of the most important experiments in neutron history
Antiferromagnetism in MnO

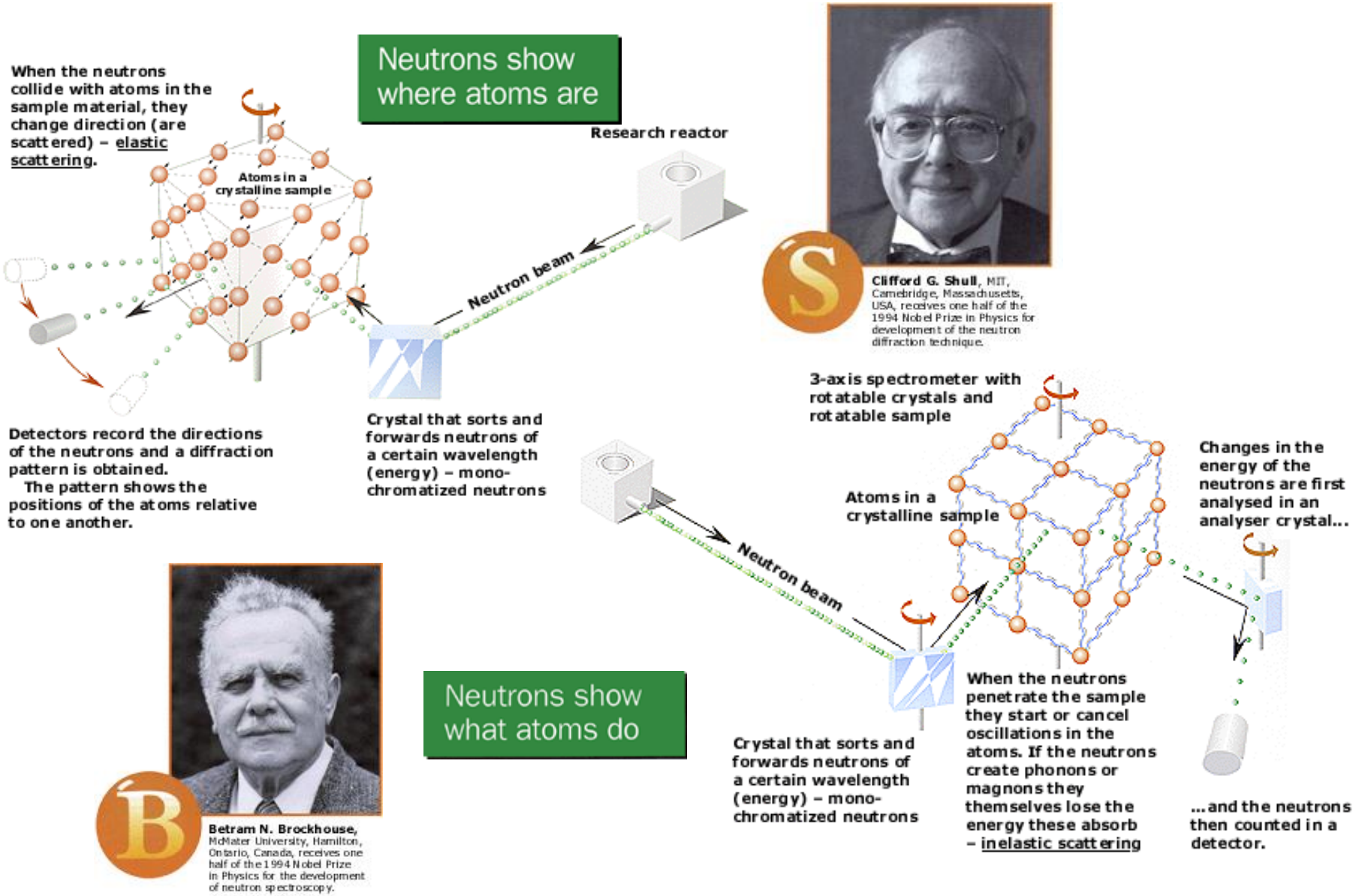




One of the most important experiments in neutron history
Roton in superfluid Helium4

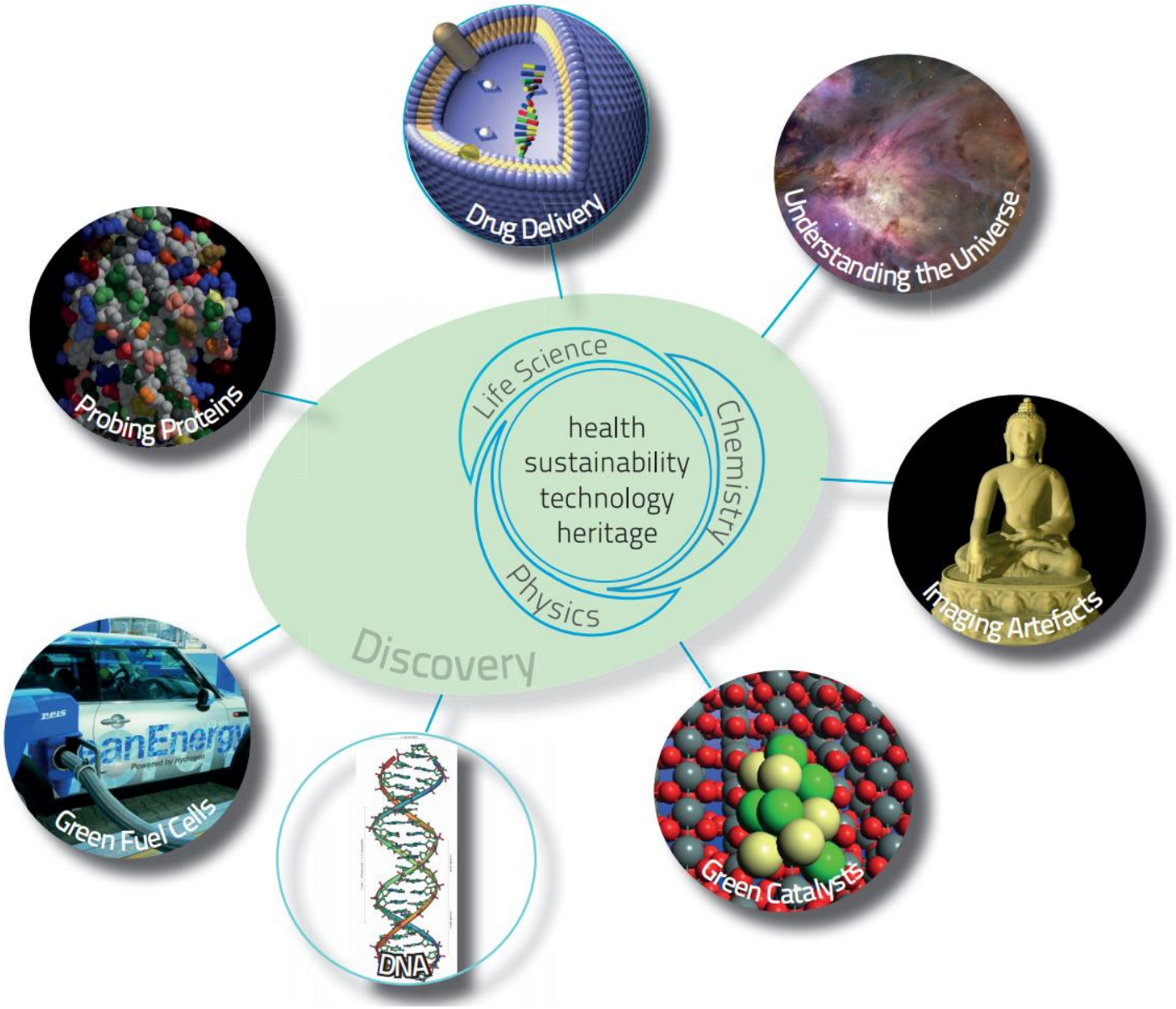


1994 Nobel Prize in Physics -- Shull and Brockhouse



http://www.nobelprize.org/nobel_prizes/physics/laureates/1994/illpres/neutrons.html

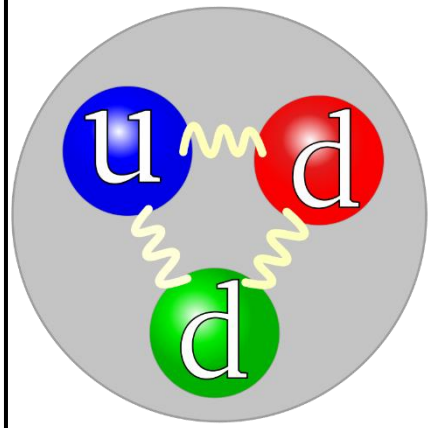
Strategic goals of Neutron scattering



Basic theory of neutron scattering

Properties of Free Neutrons

- Baryons
- Electrical Neutral (<10^{-22}e)
- Spin = ½
- Magnetic moment: -1.913 μ_N
- Mass = 939.566 MeV
- Lifetime = 880ish
- Electrical dipole moment: < 2.9x10^{-26} *e**cm



	Energy (meV)	Temp (K)	Wavelength (nm)
Cold	**0.1 – 10**	**1 – 120**	**0.4 – 3**
Thermal	**5 – 100**	**60 – 1000**	**0.1 – 0.4**
Hot	**100 – 500**	**1000 – 6000**	**0.04 – 0.1**

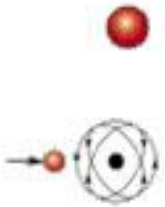
Velocity (v), kinetic energy (E), wavevector (k), wavelength (λ), temperature (T).

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

λ (nm) = 395.6 / v (m/s)

E (meV) = 0.02072 k^2 (k in nm^{-1})

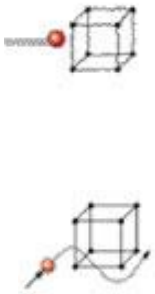
Properties of Free Neutrons



- Neutral
- Penetrating, probe nuclei
- Non-destructive

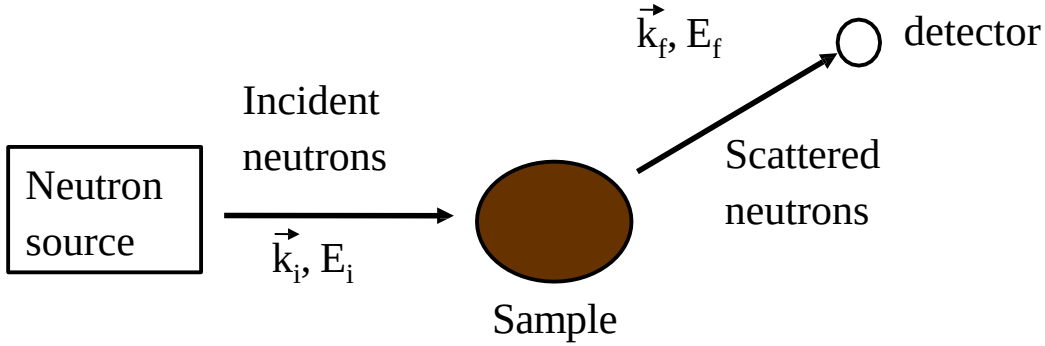


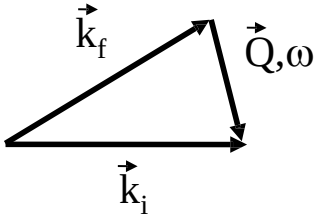
- Magnetic moment
- Magnetic fluctuations and domains
- Magnetization density
- Magnetic excitations
- **Can be polarized**



- Energy similar to excitations in solids
  - Molecular vibrations
  - Atomic motion
  - Lattice modes
- Wavelengths similar to atomic spacing
  - Crystal structures
  - Huge probe range from 10^{-13} to 10^{-4} cm

Neutron scattering events





$$\vec{Q} = \vec{k_i} - \vec{k_f}$$

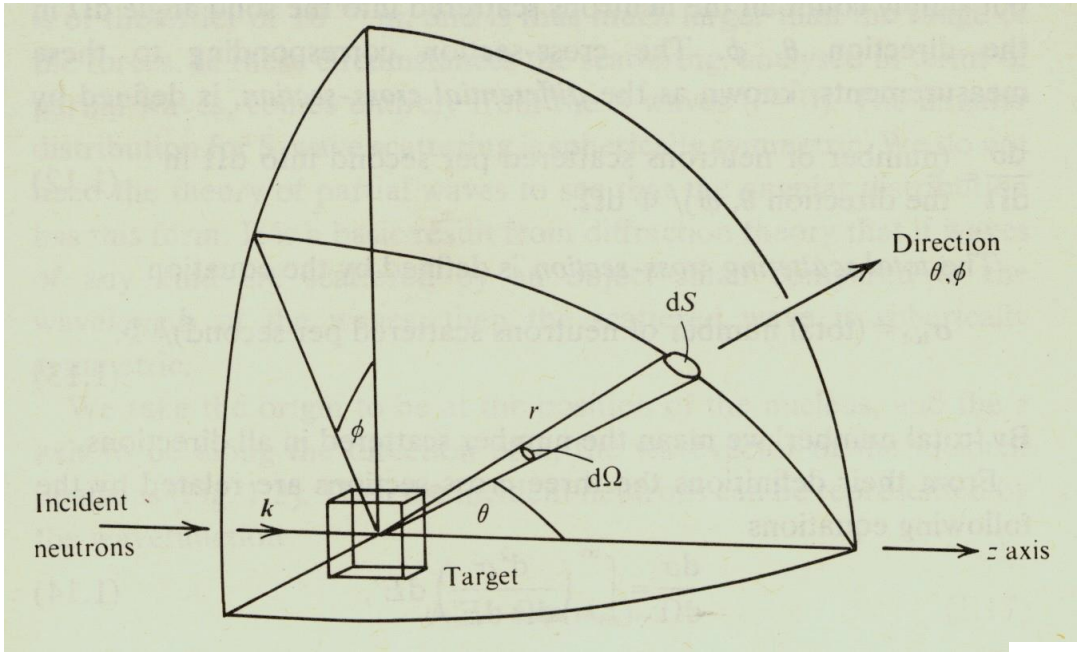
wave vector transfer

$$\hbar\omega = E_i - E_f = \frac{\hbar^2}{2m}(k_i^2 - k_f^2)$$

Energy transfer

elastic: 1-5000 Å
energy transfer: neV - eV
0 - 20000 cm^{-1}

Neutron Scattering Cross Sections



o measured in barns:
1 barn = 10^{-24} cm^2

Attenuation = exp(-Nσt)
N = # of atoms/unit volume
t = thickness

Φ = number of incident neutrons per cm^2 per second — Incident flux

σ = total number of neutrons scattered per second / Φ — total scattering cross section

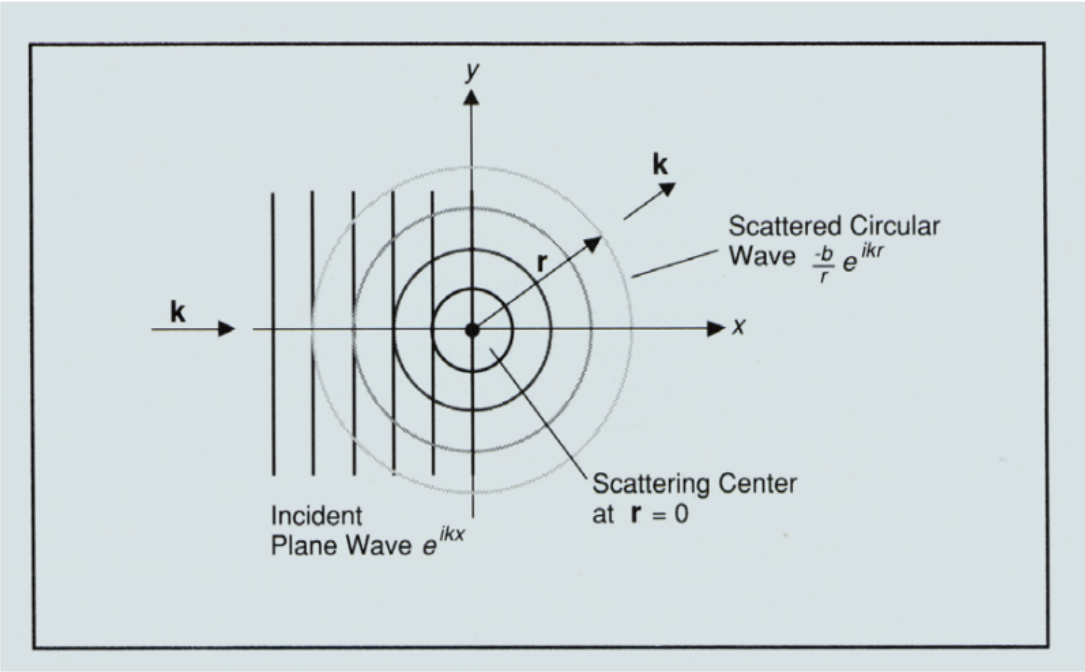
$$\frac{d\sigma}{d\Omega} = \frac{\text{number of neutrons scattered per second into } d\Omega}{\Phi\, d\Omega}$$

Differential scattering cross section

$$\frac{d^2\sigma}{d\Omega dE} = \frac{\text{number of neutrons scattered per second into } d\Omega \text{ \& } dE}{\Phi\, d\Omega dE}$$

Double-differential scattering cross section

Neutron Scattering off a (fixed) point source



- range of nuclear force (~ 1fm) is << neutron wavelength so scattering is "point-like"
- energy of neutron is too small to change energy of nucleus & neutron cannot transfer KE to a fixed nucleus => scattering is elastic
- we consider only scattering far from nuclear resonances where neutron absorption is negligible

If v is the velocity of the neutron (same before and after scattering), the number of neutrons passing through an area dS per second after scattering is :

$$v\, dS \left|\psi_{scat}\right|^2 = v\, dS\, b^2/r^2 = v\, b^2\, d\Omega$$

Since the number of incident neutrons passing through unit areas is : $\Phi = v\left|\psi_{incident}\right|^2 = v$

$$\frac{d\sigma}{d\Omega} = \frac{v\, b^2\, d\Omega}{\Phi d\Omega} = b^2 \qquad \text{so } \sigma_{total} = 4\pi b^2 \qquad \text{(note units)}$$

Adding up scattering from many (fixed) point source

At a scattering center located at $\vec{R}_i$ the incident wave is $e^{i\vec{k}_0.\vec{R}_i}$

so the scattered wave at $\vec{r}$ is $\psi_{scat} = \sum e^{i\vec{k}_0.\vec{R}_i}\left[\frac{-b_i}{|\vec{r}-\vec{R}_i|}e^{i\vec{k}'.(\vec{r}-\vec{R}_i)}\right]$

$$\therefore \frac{d\sigma}{d\Omega} = \frac{vdS|\psi_{scat}|^2}{vd\Omega} = \frac{dS}{d\Omega}\left|b_i e^{i\vec{k}'.\vec{r}}\sum\frac{1}{|\vec{r}-\vec{R}_i|}e^{i(\vec{k}_0-\vec{k}').\vec{R}_i}\right|^2$$ (using defn. from earlier VG)

If we measure far enough away so that $r >> R_i$ we can use $d\Omega = dS/r^2$ to get

$$\frac{d\sigma}{d\Omega} = \sum_{i,j} b_i b_j e^{i(\vec{k}_0-\vec{k}').(\vec{R}_i-\vec{R}_j)} = \sum_{i,j} b_i b_j e^{-i\vec{Q}.(\vec{R}_i-\vec{R}_j)}$$

where the wavevector transfer Q is defined by $\vec{Q} = \vec{k}'-\vec{k}$

Coherent and incoherent scattering

The scattering length, b_i , depends on the nuclear isotope, spin relative to the neutron & nuclear eigenstate. For a single nucleus:

$$b_i = \langle b \rangle + \delta b_i \quad \text{where } \delta b_i \text{ averages to zero}$$

$$b_i b_j = \langle b \rangle^2 + \langle b \rangle(\delta b_i + \delta b_j) + \delta b_i \delta b_j$$

$$\text{but } \langle \delta b \rangle = 0 \text{ and } \langle \delta b_i \delta b_j \rangle \text{ vanishes unless i = j}$$

$$\langle \delta b_i^2 \rangle = \langle b_i - \langle b \rangle \rangle^2 = \langle b^2 \rangle - \langle b \rangle^2$$

$$\therefore \frac{d\sigma}{d\Omega} = \langle b \rangle^2 \sum_{i,j} e^{-i\vec{Q}.(\vec{R}_i - \vec{R}_j)} + (\langle b^2 \rangle - \langle b \rangle^2) N$$

Coherent Scattering
(scattering depends on the direction & magnitude of **Q**)

Incoherent Scattering
(scattering is uniform in all directions)

Note: N = number of atoms in scattering system

Coherent and incoherent scattering - some numbers

Nuclide	σ_{coh}	σ_{inc}	Nuclide	σ_{coh}	σ_{inc}
^{1}H	1.8	80.2	V	0.02	5.0
^{2}H	5.6	2.0	Fe	11.5	0.4
C	5.6	0.0	Co	1.0	5.2
O	4.2	0.0	Cu	7.5	0.5
Al	1.5	0.0	^{36}Ar	24.9	0.0

- Difference between H and D used in experiments with soft matter (contrast variation)
- Al used for windows
- V used for sample containers in diffraction experiments and as calibration for energy resolution
- Fe and Co have nuclear cross sections similar to the values of their magnetic cross sections
- Find scattering cross sections at the NIST web site at:

  http://webster.ncnr.nist.gov/resources/n-lengths/

Coherent elastic scattering -- S(Q), structure factor

$$\frac{d\sigma}{d\Omega} = \langle b \rangle^2 N.S(\vec{Q}) \quad \text{for an assembly of similar atoms where} \quad S(\vec{Q}) = \frac{1}{N}\left\langle \sum_{i,j} e^{-i\vec{Q}.(\vec{R}_i - \vec{R}_j)} \right\rangle_{\text{ensemble}}$$

Now $\sum_i e^{-i\vec{Q}.\vec{R}_i} = \int d\vec{r}.e^{-i\vec{Q}.\vec{r}} \sum_i \delta(\vec{r} - \vec{R}_i) = \int d\vec{r}.e^{-i\vec{Q}.\vec{r}} \rho_N(\vec{r})$ where ρ_N is the nuclear number density

so $$S(\vec{Q}) = \frac{1}{N}\left\langle \left| \int d\vec{r}.e^{-i\vec{Q}.\vec{r}} \rho_N(\vec{r}) \right|^2 \right\rangle$$

or $$S(\vec{Q}) = \frac{1}{N}\int d\vec{r}' \int d\vec{r}.e^{-i\vec{Q}.(\vec{r}-\vec{r}')} \langle \rho_N(\vec{r}) \rho_N(\vec{r}') \rangle = \frac{1}{N}\int d\vec{R} \int d\vec{r} e^{-i\vec{Q}.\vec{R}} \langle \rho_N(\vec{r}) \rho_N(\vec{r} - \vec{R}) \rangle$$

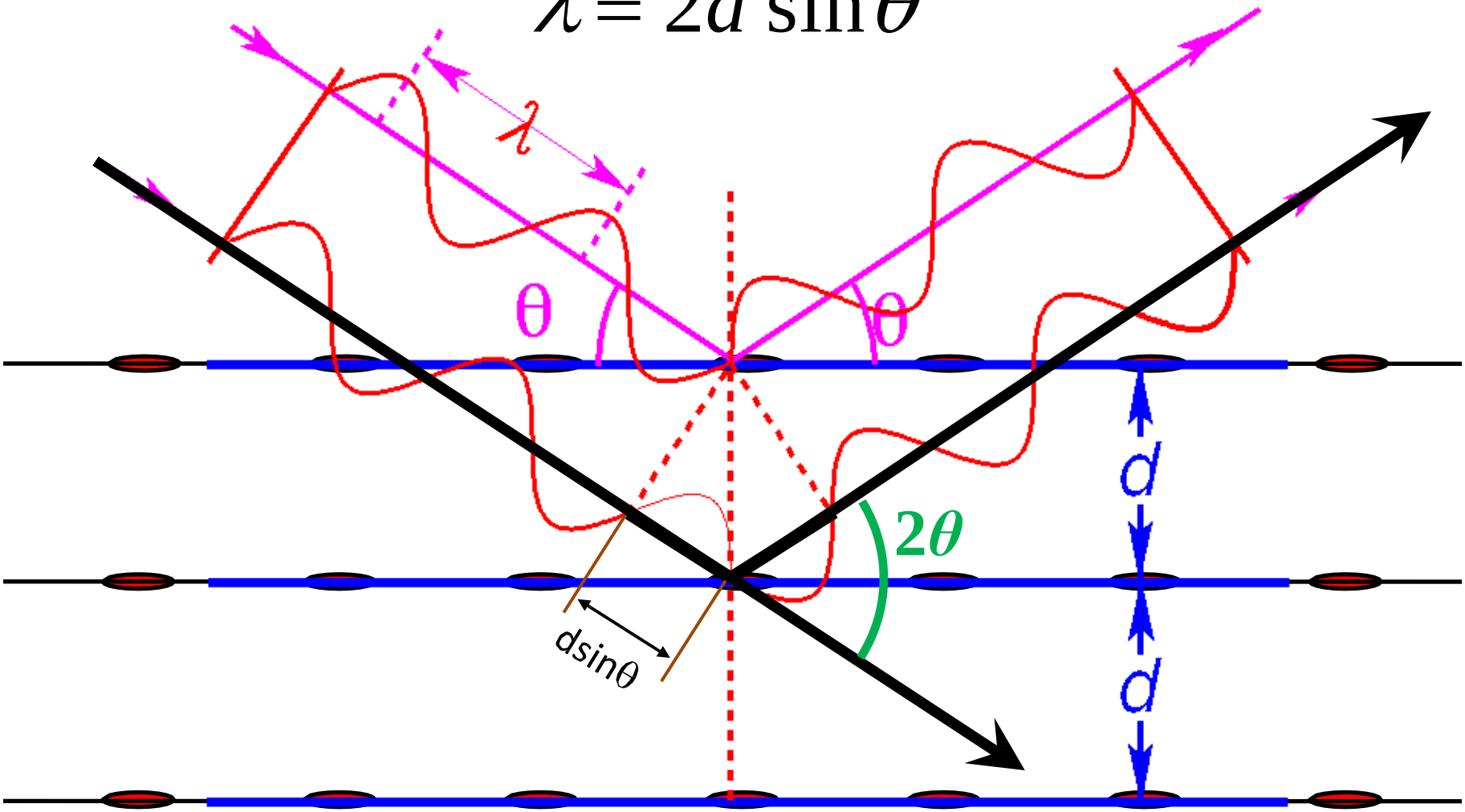
ie $$S(\vec{Q}) = 1 + \int d\vec{R}.\{g(\vec{R}) - \overline{\rho}\}.e^{-i\vec{Q}.\vec{R}}$$

where $g(\vec{R}) = \sum_{i \neq 0} \langle \delta(\vec{R} - \vec{R}_i + \vec{R}_0) \rangle$ is a function of $\vec{R}$ only.

g(R) is known as the **static pair correlation function**. It gives the probability that there is an atom, i, at distance R from the origin of a coordinate system, given that there is also a (different) atom at the origin of the coordinate system at the same instant in time.

Neutron Diffraction: Bragg's Law

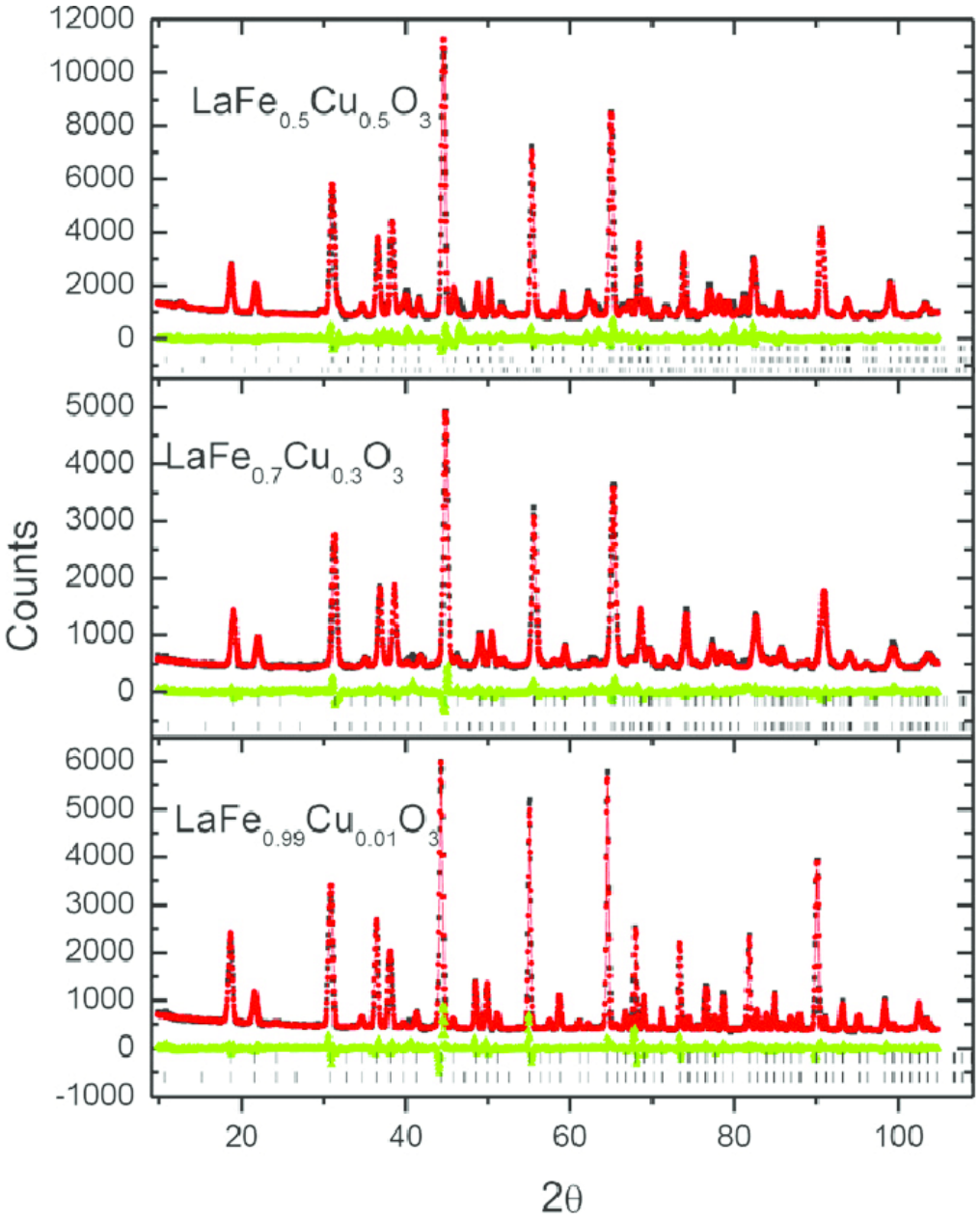
$$\lambda = 2d \sin\theta$$



Diffraction -- What can we learn from it?

- Are there peaks? (Crystallinity)
- Which crystalline phases are present? (Phase identification, database of fingerprint patterns)
- How many crystalline phases are present? (Homogeneity)
- Relative amount of phases? (Quantitative phase analysis)
- Crystal structure refinement
- Size, strain

A Typical powder diffraction pattern



Inelastic scattering -- Atoms are not fixed

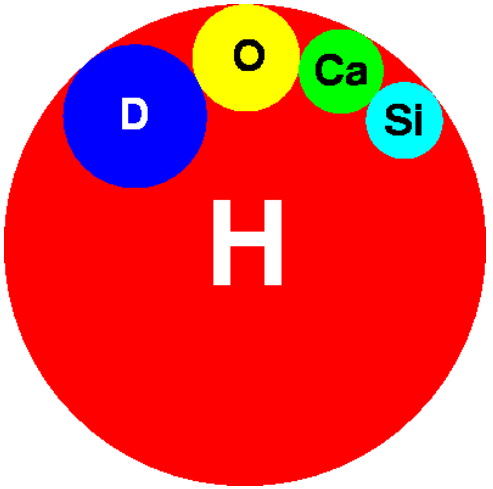
- **The formalism on the previous slide works fine if the atoms are stationary: in reality, they are not**
- **Remember that** $S(\vec{Q}) = \frac{1}{N}\left\langle \sum_{i,j} e^{-i\vec{Q}.(\vec{R}_i - \vec{R}_j)} \right\rangle_{\text{ensemble}}$
- **We average over the (fluctuating) atomic positions by introducing a probability that an atom will be at given position. Instead of the Fourier Transform of δ functions, this gives the FT of the δ functions *convolved* with a spread function. The result is that S(Q) is *multiplied* by the FT of the spread function i.e. by** $\exp -Q^2\left\langle u^2 \right\rangle / 3$ **if we use a Gaussian spread function**

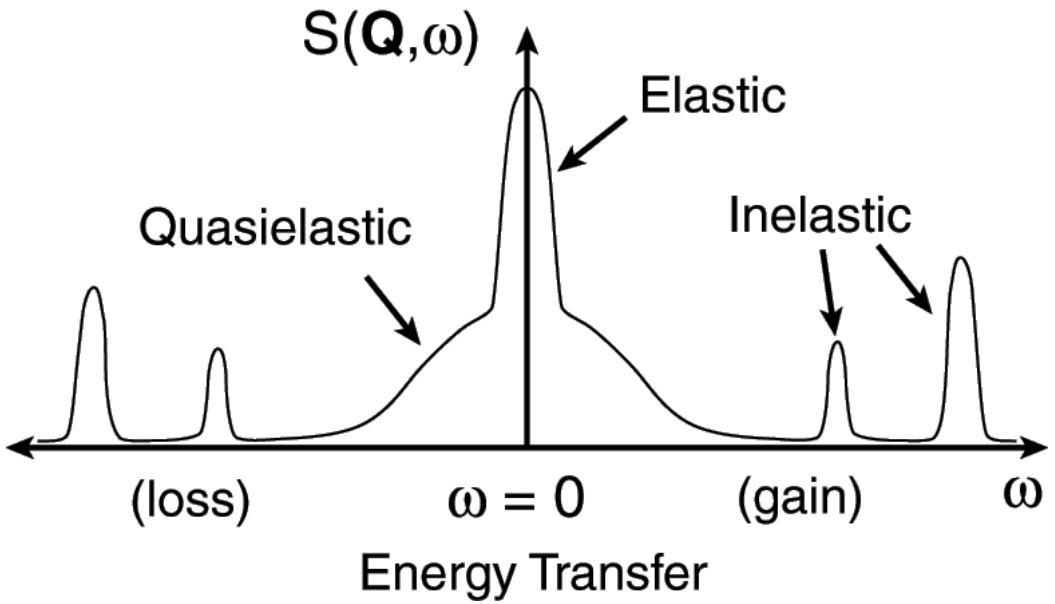


- **Atomic vibrations cause a decrease in the intensity of Bragg scattering. The "missing" scattering appears between Bragg peaks and results in inelastic scattering**

Inelastic scattering

For systems containing a reasonable proportion of H atoms, scattering from H tends to dominate.





Measure scattered neutrons as function of Q and ω: S(Q, ω)

ω = 0: Elastic

ω ≠ 0: Inelastic

ω ≈ 0: Quasi-elastic

Inelastic scattering -- coherent and incoherent

In term of the pair correlation functions, one finds

$$\left(\frac{d^2\sigma}{d\Omega.dE}\right)_{coh} = b_{coh}^2 \frac{k'}{k} NS(\vec{Q},\omega)$$

$$\left(\frac{d^2\sigma}{d\Omega.dE}\right)_{inc} = b_{inc}^2 \frac{k'}{k} NS_s(\vec{Q},\omega)$$

$(h/2\pi)\mathbf{Q}$ & $(h/2\pi)\omega$ are the momentum & energy transferred to the neutron during the scattering process

where

$$S(\vec{Q},\omega) = \frac{1}{2\pi\hbar}\iint G(\vec{r},t)e^{i(\vec{Q}.\vec{r}-\omega t)}d\vec{r}dt \quad \text{and} \quad S_s(\vec{Q},\omega) = \frac{1}{2\pi\hbar}\iint G_s(\vec{r},t)e^{i(\vec{Q}.\vec{r}-\omega t)}d\vec{r}dt$$

- Inelastic coherent scattering measures *correlated* motions of different atoms
- Inelastic incoherent scattering measures *self-correlations* e.g. diffusion

To Summarize

- The intensity of elastic, coherent neutron scattering is proportional to the spatial Fourier Transform of the Pair Correlation Function, G(r) I.e. the probability of finding a particle at position r if there is simultaneously a particle at r=0

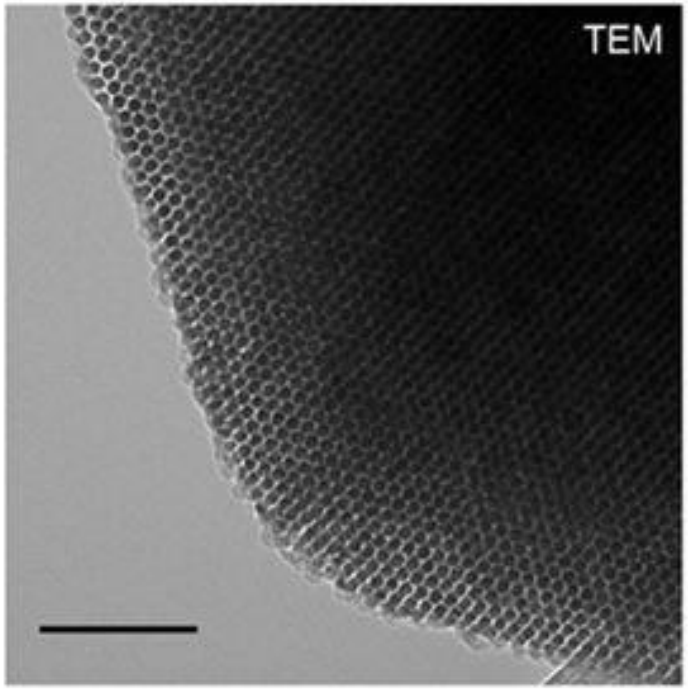
- The intensity of inelastic coherent neutron scattering is proportional to the space *and time* Fourier Transforms of the *time-dependent* pair correlation function function, G(r,t) = probability of finding a particle at position r *at time t* when there is a particle at r=0 and *t=0*.

- For inelastic *incoherent* scattering, the intensity is proportional to the space and time Fourier Transforms of the *self-correlation* function, $G_s(r,t)$ I.e. the probability of finding a particle at position r at time t when *the same* particle was at r=0 at t=0

X ray scattering vs. neutron scattering

研究微观世界的方法

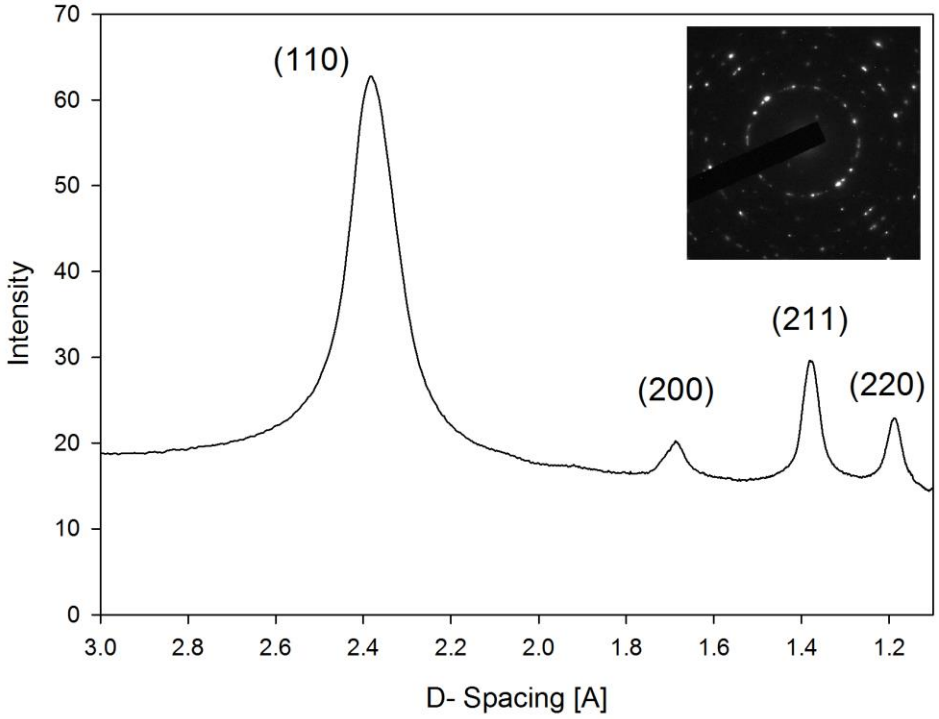
Microscope
实空间



电子显微镜下硅纳米管

optical，electron，scanning probe

Scattering
倒空间

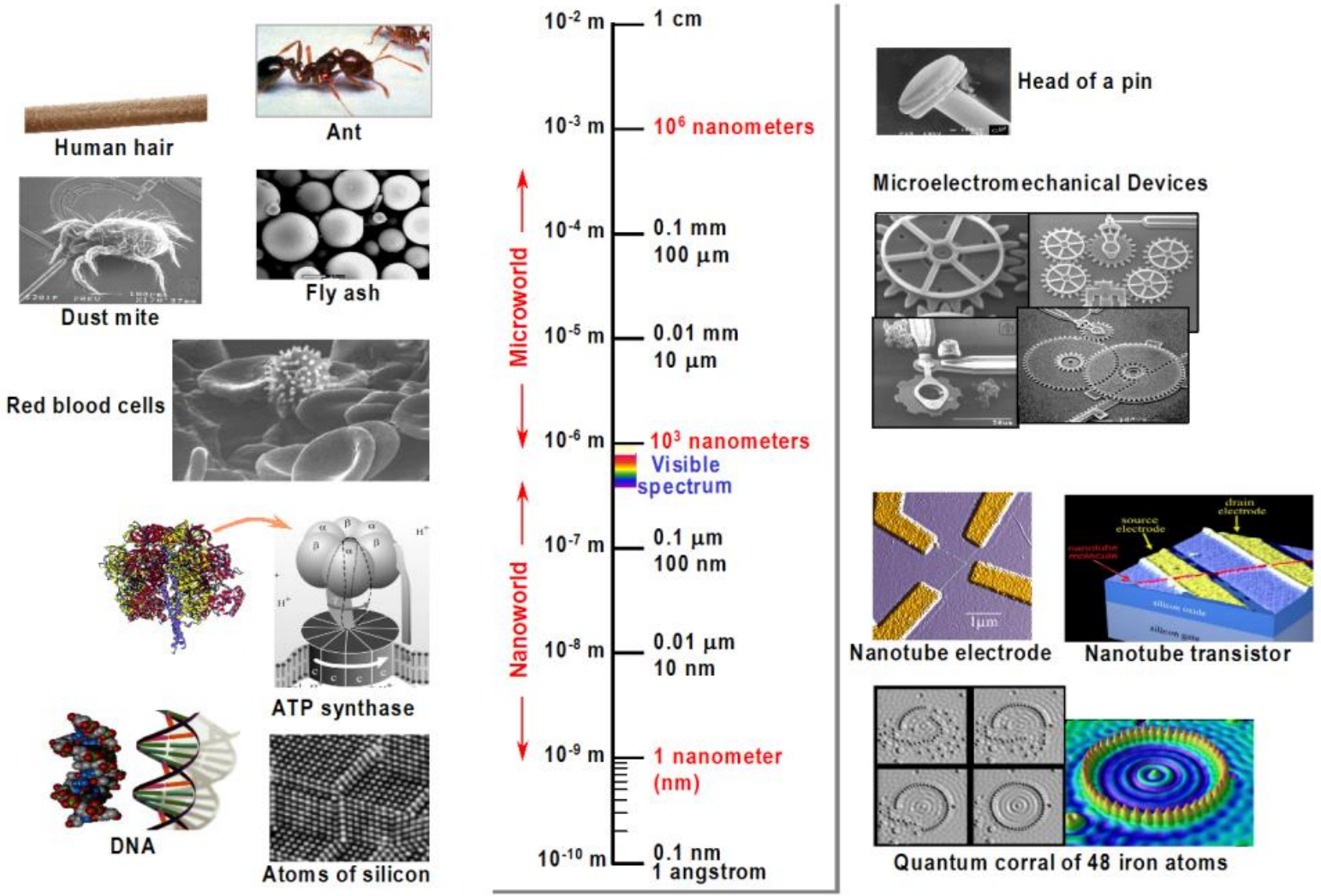


硅单晶的衍射图

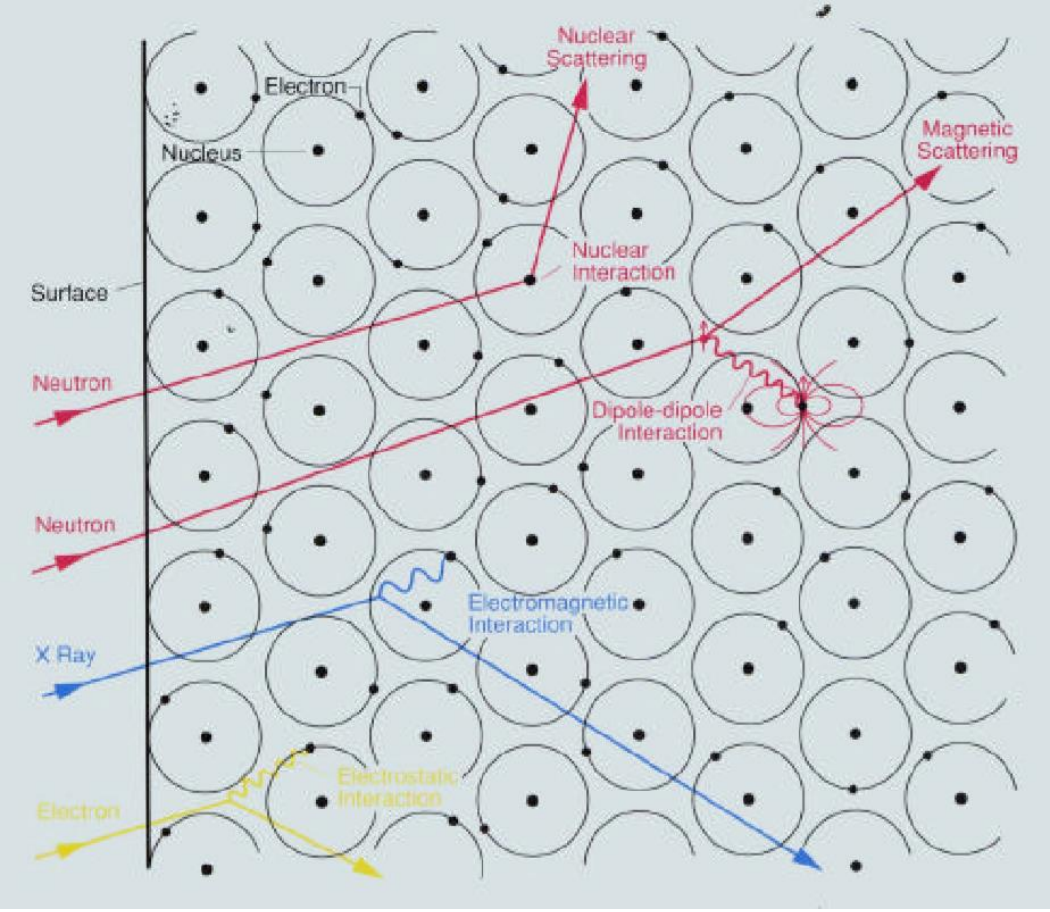
light, electron, **X-ray**, **Neutron**

X-ray and Neutron scattering as a tool

Nanoscale science and technology presents extraordinary opportunities

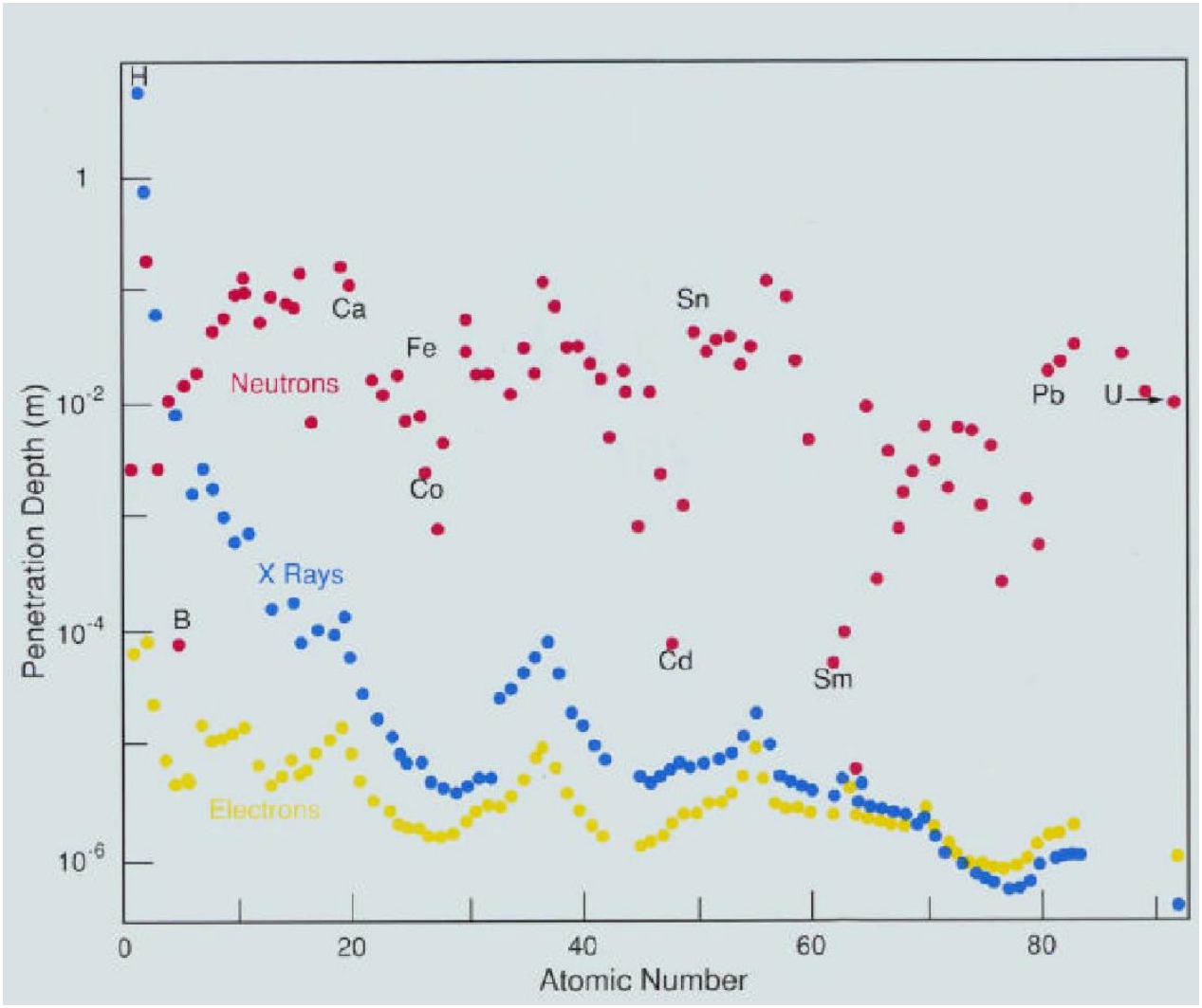


Neutrons vs. X-rays! – Interactions with matter



- Neutrons interact with atomic nuclei via very short range (~fm) forces.
- Neutrons also interact with unpaired electrons via a magnetic dipole interaction.

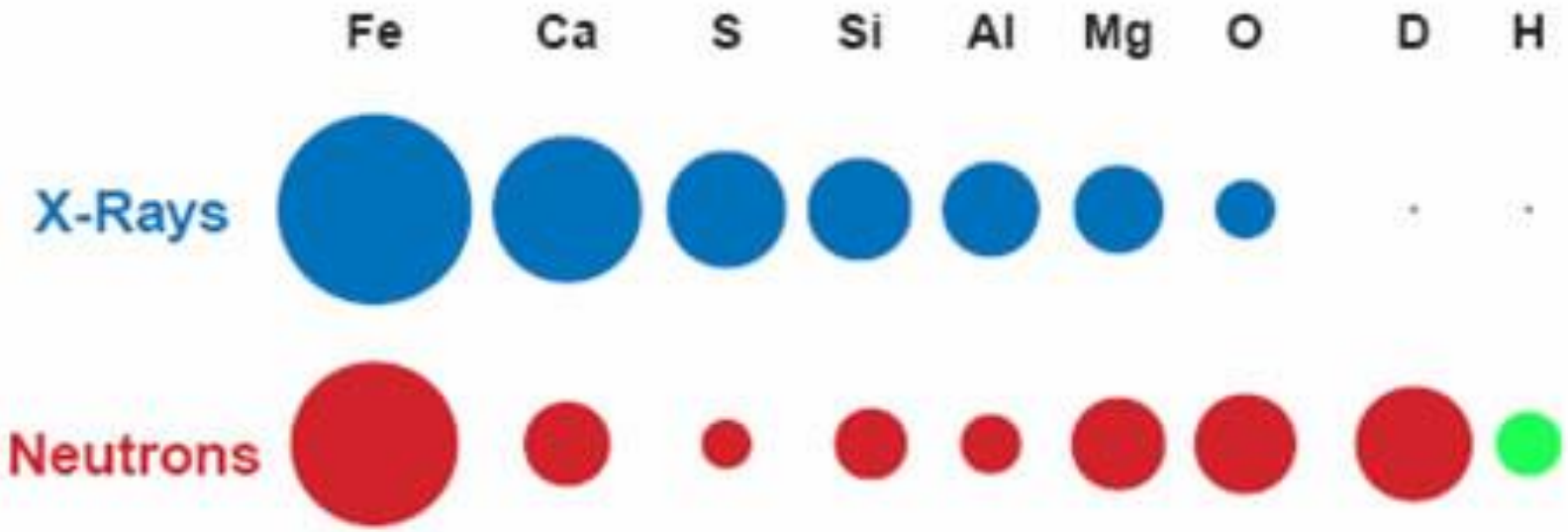
Neutrons vs. X-rays! -- Penetration depth



Note for neutrons:

- H/D difference
- Cd, B, Sm
- No systematic Z dependence

Neutrons vs. X-rays! – Scattering length



- Can be precisely calculated
- Sees light elements (H, Li etc.)
- Can discriminate adjacent elements
- Can discriminate isotopes

Neutrons vs. X-rays! – Brightness and Flux

	Brightness ($s^{-1}\ m^{-2}\ ster^{-1}$)	*dE/E* (%)	*Divergence* ($mrad^2$)	*Flux* ($s^{-1}\ m^{-2}$)
Neutrons	10^{15}	2	10 x 10	10^{11}
Rotating Anode	10^{16}	3	0.5 x 10	5×10^{10}
Bending Magnet	10^{24}	0.01	0.1 x 5	5×10^{17}
Wiggler	10^{26}	0.01	0.1 x 1	10^{19}
Undulator (APS)	10^{33}	0.01	0.01 x 0.1	10^{24}

Neutron scattering: Pros and Cons

Pros

- Wavelength comparable with interatomic spacings ~A
- Kinetic energy comparable with that of atoms in a solid ~meV
- Penetrating
  - Bulk properties, up to 10cm samples
  - Complex sample environment
- Weak interaction with matter
  - Mostly s-wave
  - Can be precisely calculated
- Isotopic sensitivity allows contrast variation
  - Isotope scattering differently
  - H, D scattering drastically different
- Neutron magnetic moment couples to B
  - Neutron sees unpaired electron spins
  - Polarized Neutrons

Cons

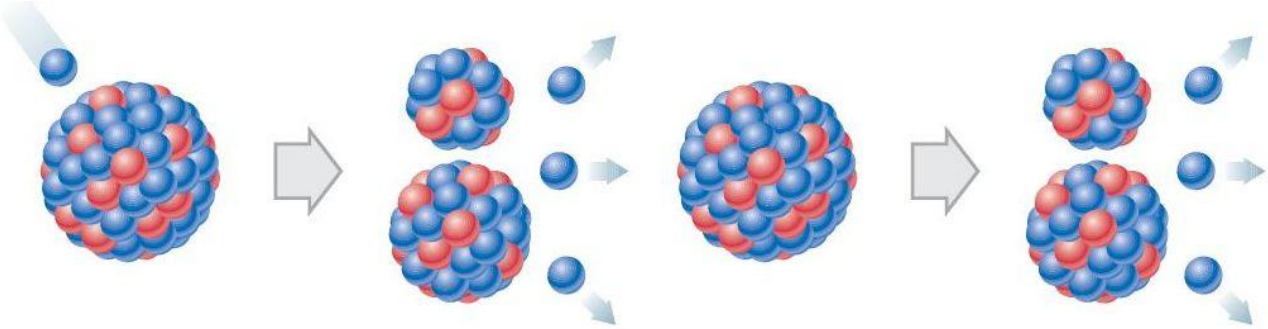
- Low flux --> weak signal --> need large sample and long data collecting time
- Some elements (e.g. Cd, B, Gd) absorb strongly

Neutron production and neutron facilities

Production of free neutrons -- Fission and Spallation

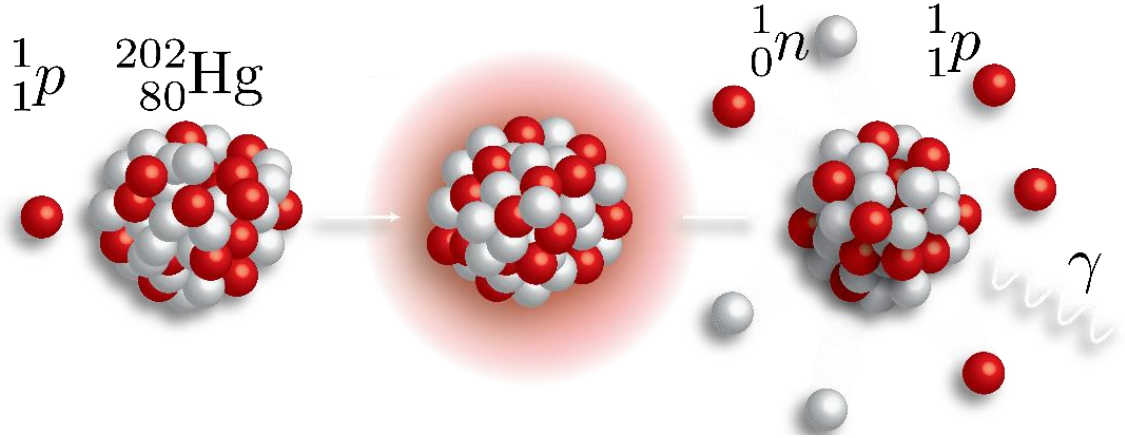
Fission Reactors

- Chain reaction
- Continuous
- 2-3 neutrons/fission
- ~180MeV/neutron

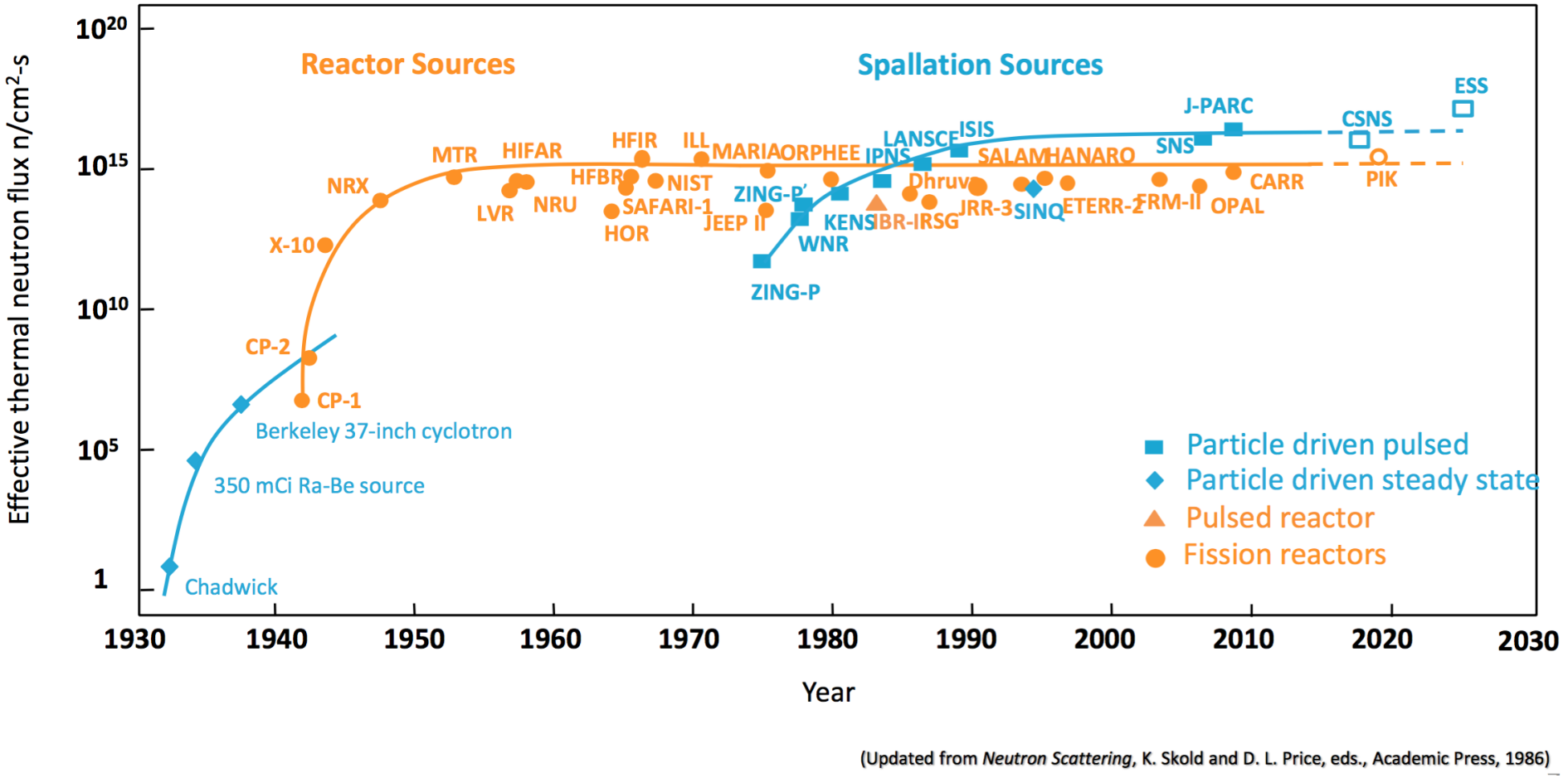


Spallation

- No chain reaction
- Pulsed
- 30-40 neutrons/proton
- ~30MeV/neutron
- 4 in the world



Source vs. Flux

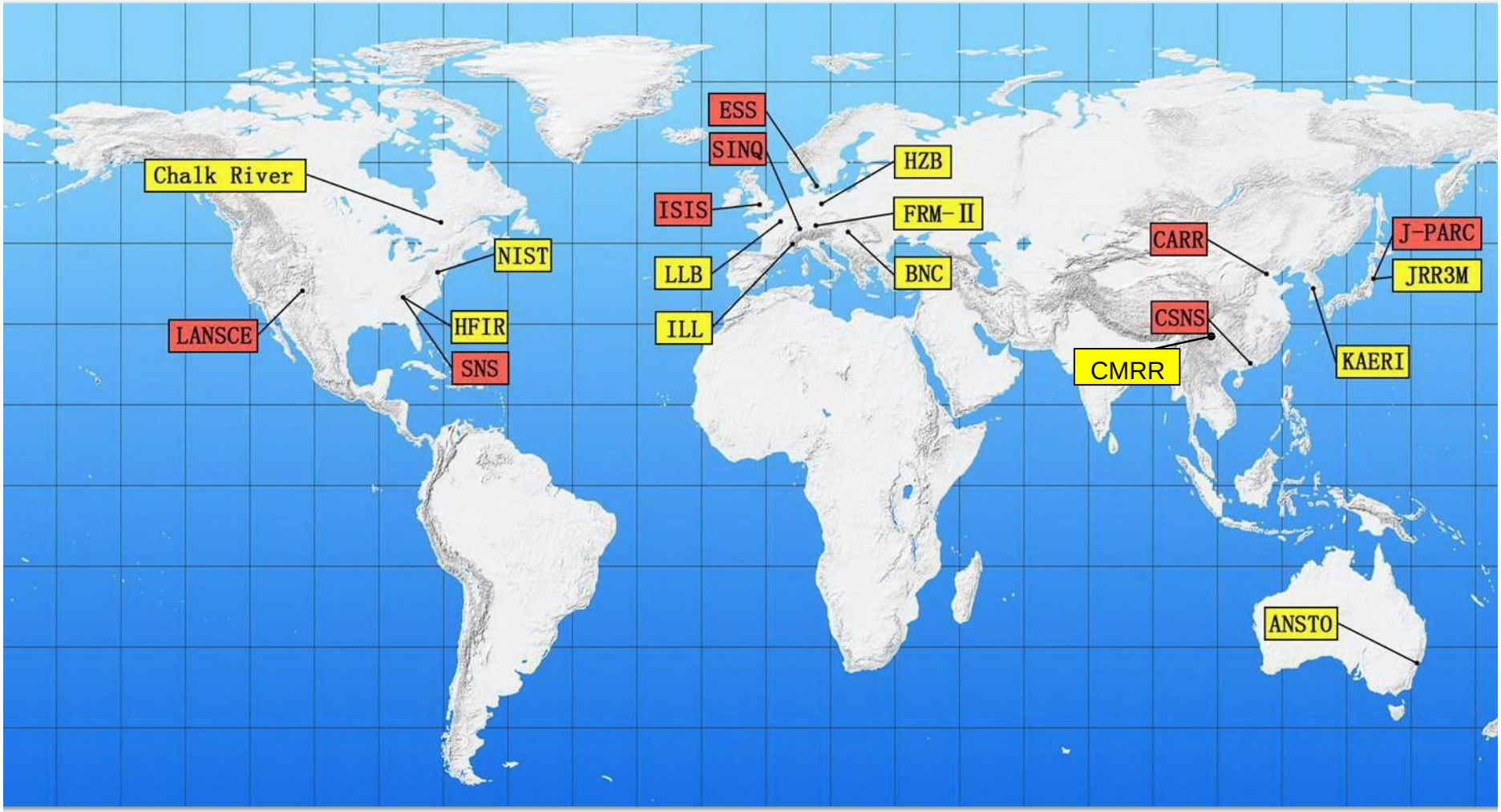


(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

From: ESS – Status and Prospects, Ciprian Plostinar, Aug.2018

37

Major Neutron Facilities in the World



SNS, HFIR
Oak Ridge National Laboratory



High Flux Reactor
Power: 85MW
First in critical: 1965



Spallation Neutron Source
Initial Budget: 1.4b USD
Completion date: Apr 2006

中国中子源大科学装置

反应堆

散裂源



中国散裂中子源基本信息

- 主管部门：中国科学院
- 共建部门：广东省人民政府
- 法人单位：高能物理研究所
- 共建单位：物理研究所

- 批复概算： 18.6632亿元
- 建设选址：广东省东莞市大朗镇
- 开工时间：2011年9月
- 建设周期：6.5年，2018年3月完工



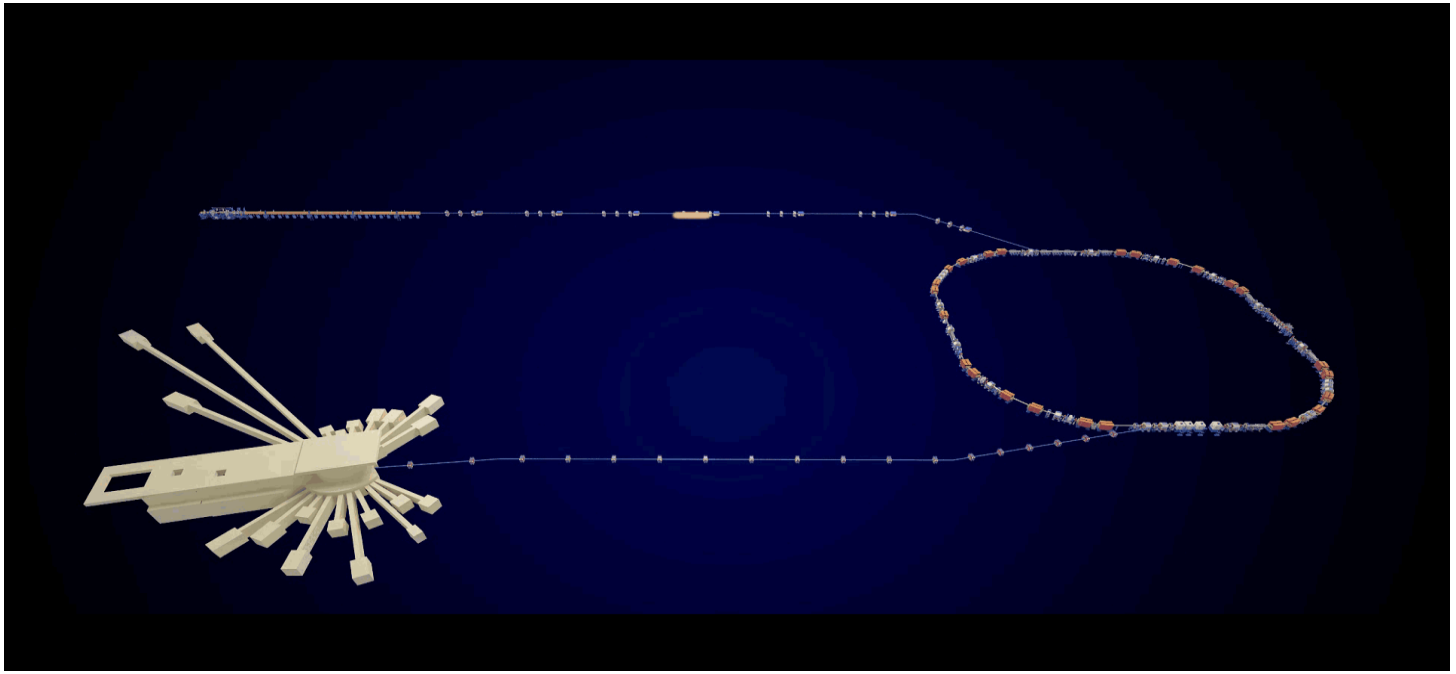
2011年10月20日中国散裂中子源奠基



2018年8月23日通过国家验收

建设内容

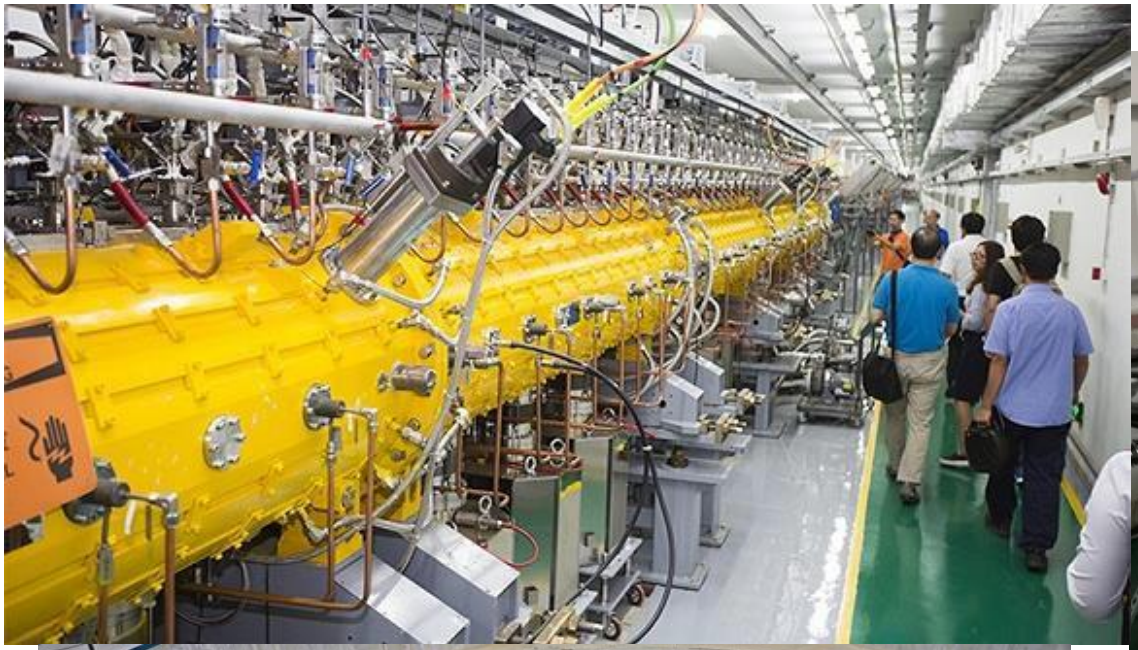
根据《国家发展改革委关于散裂中子源国家重大科技基础设施项目可行性报告的批复》，主要建设1台80MeV负氢离子直线加速器、1台1.6GeV快循环同步加速器、2条束流输运线、1个靶站、3台中子谱仪及配套设施和土建工程。



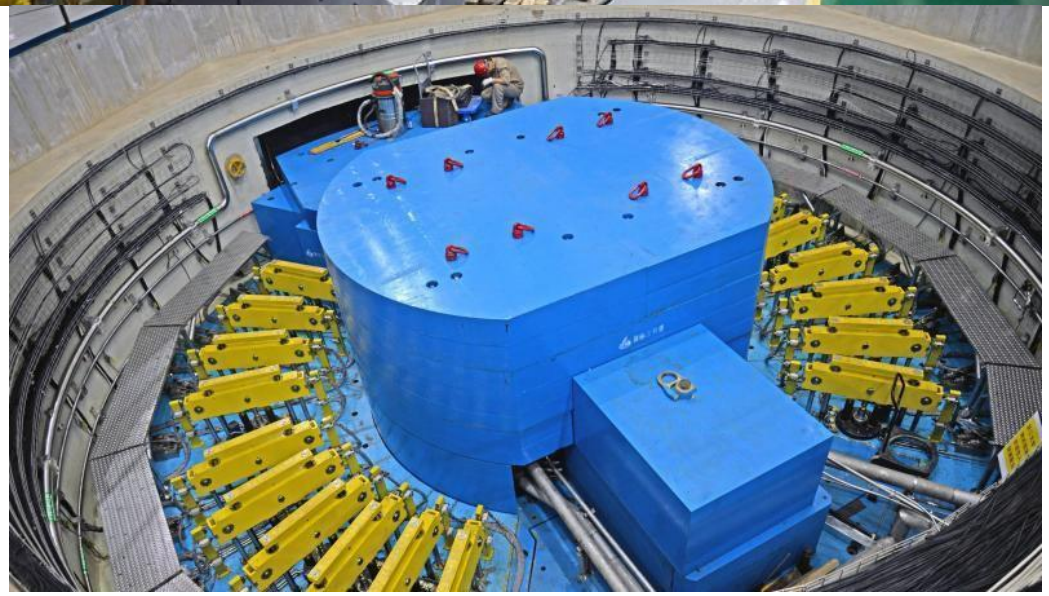
中国散裂中子源， 2018年



Linac，the ring，and the target



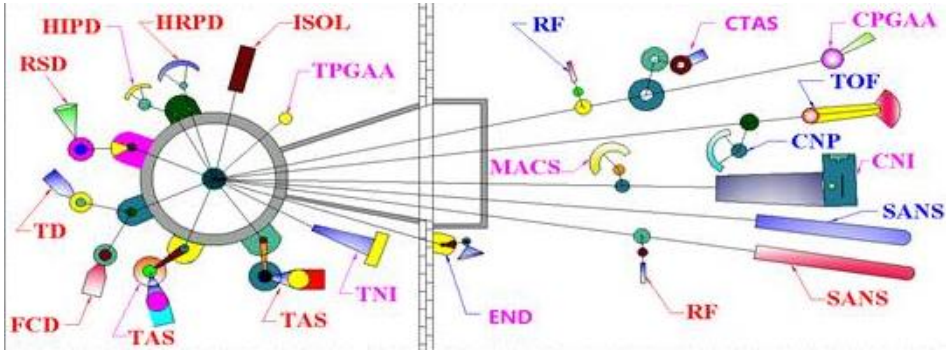




Other neutron facilities in China - CARR



The China Advanced Research Reactor (CARR) is a high-flux and multipurpose research reactor, located at the campus of China Institute of Atomic Energy(CIAE) in Beijing. It is a tank-in-pool inverse neutron trap type reactor with a power of 60MW. The peak flux in a heavy-water reflector is about 8.0×10^14 n/cm2/s. CARR went first critical on May 13th 2010 and reached the full power for 72 hours on March 13th 2012. Now it is waiting for the official permission to start the regular operation.



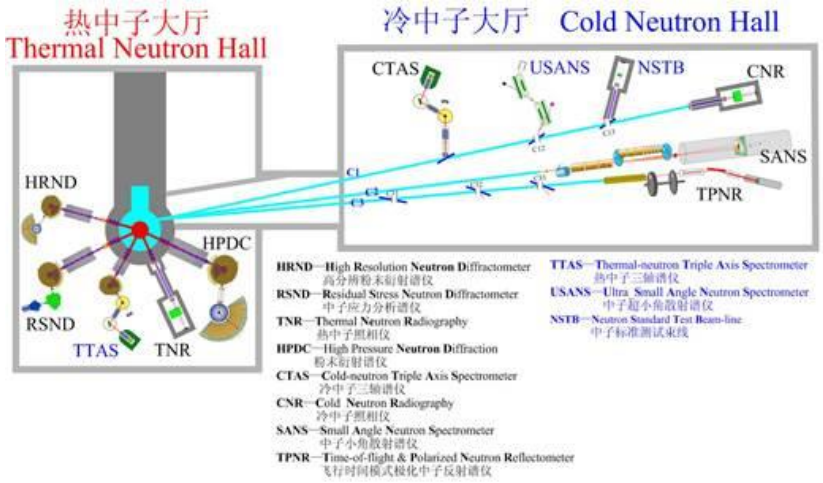
High Resolution Powder Diffractometer (HRPD), a High Intensity Powder Diffractometer (HIPD) a Residual Stress Diffractometer (RSD), a texture diffractometer (TD), a four circle diffractometer (FCD), two Triple Axis Spectrometers (TAS), a reflectometer (RF), a Small Angle Neutron Scattering instrument (SANS) were constructed.

http://english.ihep.cas.cn/ls/cnss/zzsszz/201406/t20140620_123024.html

Other neutron facilities in China - CMRR



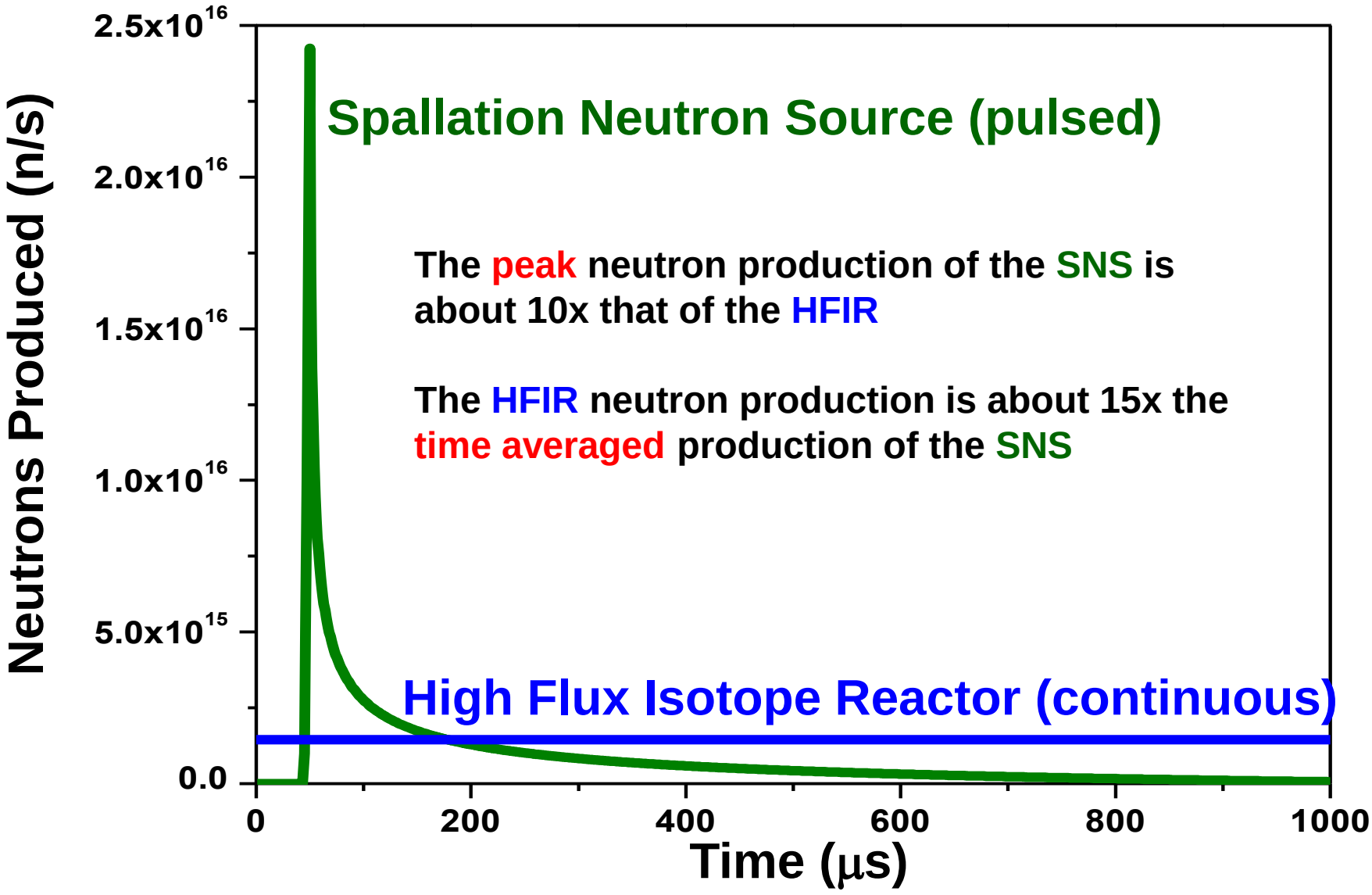
The China Mianyang Research Reactor (CMRR) with the power of 20 MW is located in the NP campus of Institute of Nuclear Physics and Chemistry, Mianyang city, Sichuan Province. It was open to users officially from 2012, including the thermal and cold neutron halls. The liquid hydrogen cold neutron source began to work from September 2013. The measured thermal and cold fluxes for neutron scattering experiments are 2.4×10^14 n/cm2·s and 10^9 n/cm2·s, respectively.



A high resolution neutron diffractometer (HRND), a residual stress neutron diffractometer (RSND), a thermal neutron radiography station (TNR) and a high pressure neutron diffractometer (HPDC). Four cold neutron instruments were installed in the guide hall: a small-angle neutron spectrometer (SANS), a time-of-flight and polarized neutron reflectometer (TPNR), a cold-neutron triple-axis spectrometer (CTAS) and a cold neutron radiography station (CNR).

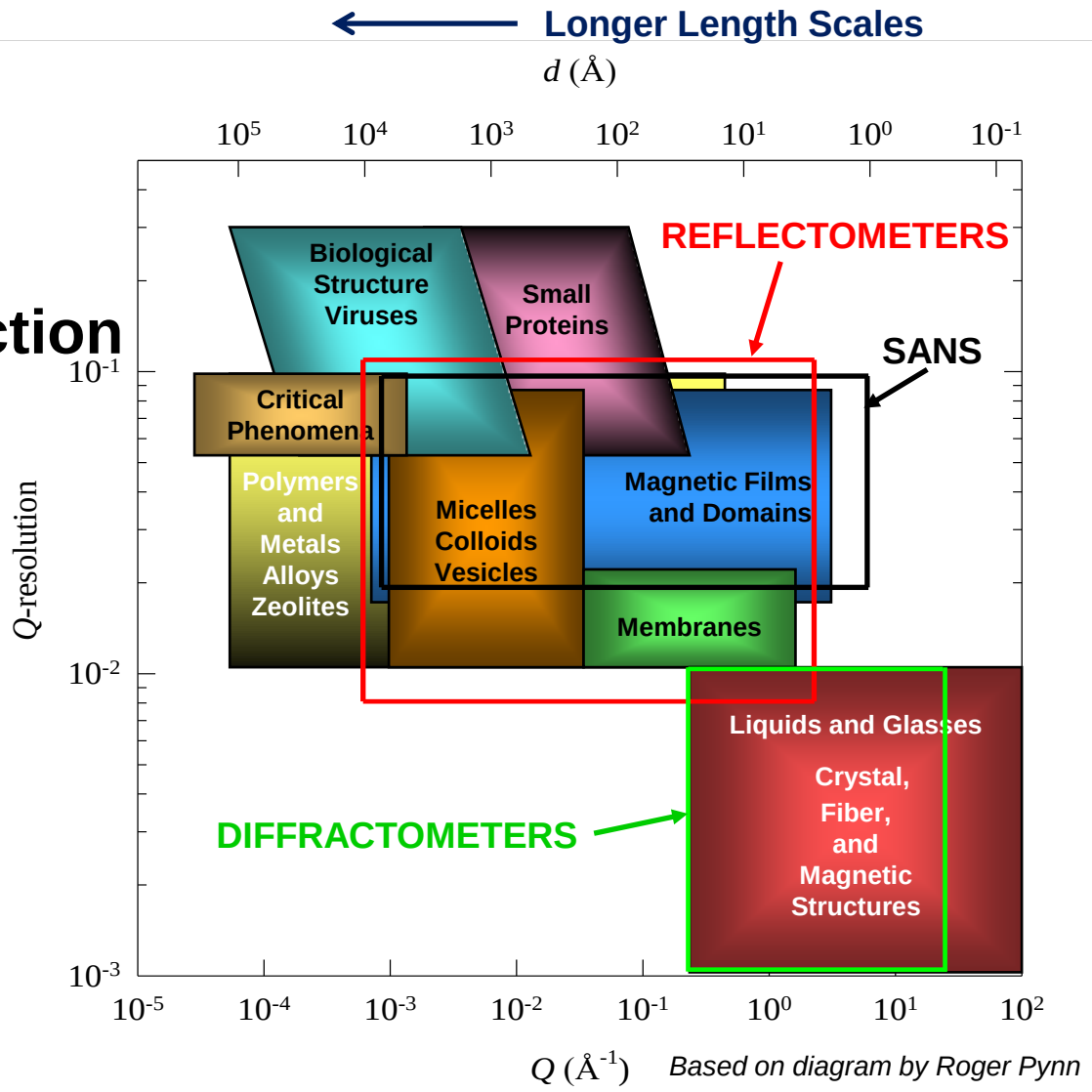
http://english.ihep.cas.cn/ls/cnss/zzsszz/201406/t20140620_123024.html

Pulsed vs Continuous Apples vs Oranges



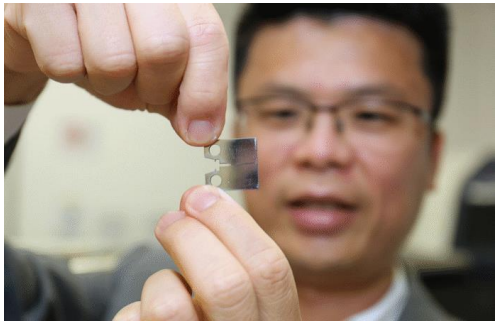
Elastic Neutron Scattering Instruments

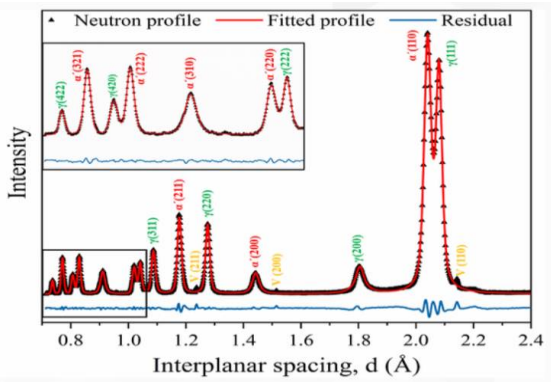
- **Elastic instruments include:**
  - **Powder diffraction**
  - **Single Crystal diffraction**
  - **SANS (typical)**
  - **Reflectometry**
- **Used to determine the average structure of materials (i.e. how the atoms are arranged)**



TOF Powder Diffractometer: GPPD(CSNS)

- Low-cost D&P steel with high yield strength (~2 GPa), excellent toughness (102 MPa· M1/2), and good ductility (19% uniform elongation) from Hongkong University.
- Important microscopic parameter information such as phase volume fraction and dislocation density was obtained through neutron diffraction @GPPD





Science

REPORTS

Cite as: L. Liu *et al.*, *Science* 10.1126/science.aba9413 (2020).

Making ultrastrong steel tough by grain-boundary delamination

L. Liu[1]*, Qin Yu[2]*, Z. Wang[1], Jon Ell[2,3], M. X. Huang[1]†, Robert O. Ritchie[2,3]†

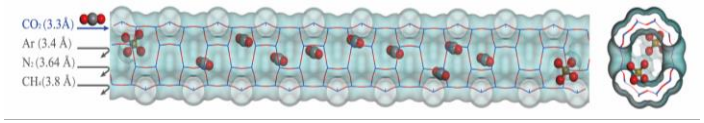
[1]Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China. [2]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA. [3]Department of Materials Science and Engineering, University of California, Berkeley, CA 94720, USA.

Liu *et.al.* Science 2020, 368, 1347-1352

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TOF Powder Diffractometer: GPPD(CSNS)

- Neutron Diffraction @ GPPD determines the fine structure of carbon dioxide in iron-containing mordenite, which has record high of carbon dioxide uptakes.

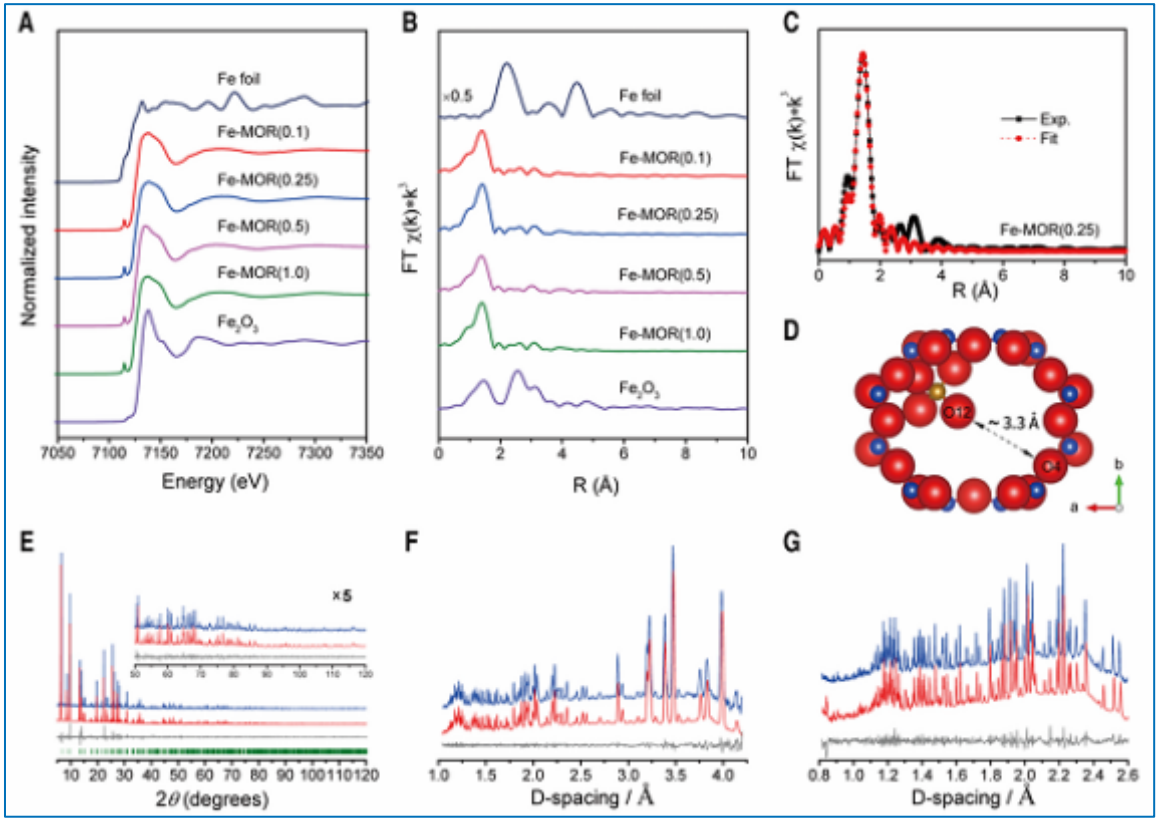


RESEARCH

GAS SEPARATION

Self-assembled iron-containing mordenite monolith for carbon dioxide sieving

Yu Zhou[1]†, Jianlin Zhang[1]†, Lei Wang[2]†, Xili Cui[3,4]†, Xiaoling Liu[1]†, Sie Shing Wong[5,6], Hua An[5,6], Ning Yan[5]*, Jingyan Xie[1], Cong Yu[3], Peixin Zhang[3], Yonghua Du[7,8], Shibo Xi[7], Lirong Zheng[9], Xingzhong Cao[10], Yajing Wu[2], Yingxia Wang[11], Chongqing Wang[1], Haimeng Wen[1], Lei Chen[1], Huabin Xing[3,4]*, Jun Wang[1]*



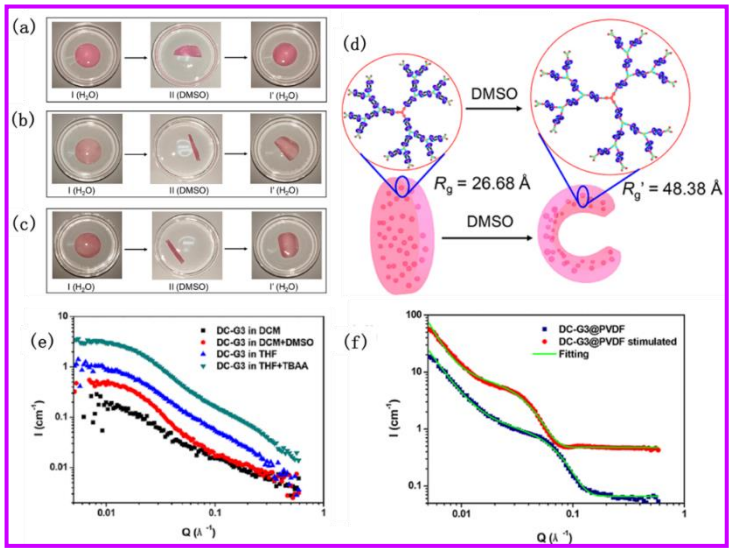
Zhou *et.al.* Science, 2021,373,315-320

Small Angle Neutron Scattering (SANS)

新型高分子聚合物

雏菊链树状分子运动行为

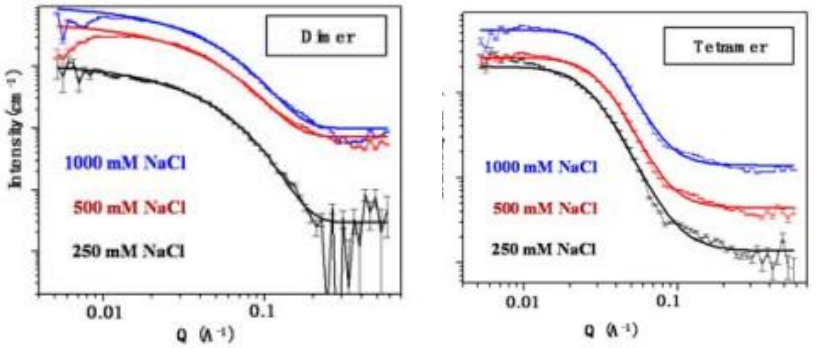
刺激后每个枝杈的折叠导致整体尺寸的可控可逆变化



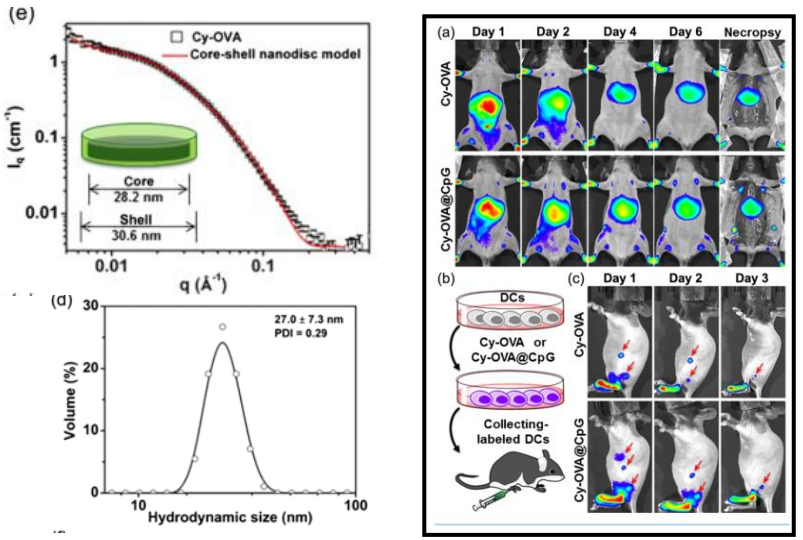
J. Am.Chem. Soc. 2020, 142, 18, 8473–8482

蛋白质及纳米药物

SARS-CoV-2 nsp8蛋白二聚体和四聚体在不同盐浓度中的稳定性和相分离行为



Communications Biology, 2022, 5(1): 925.

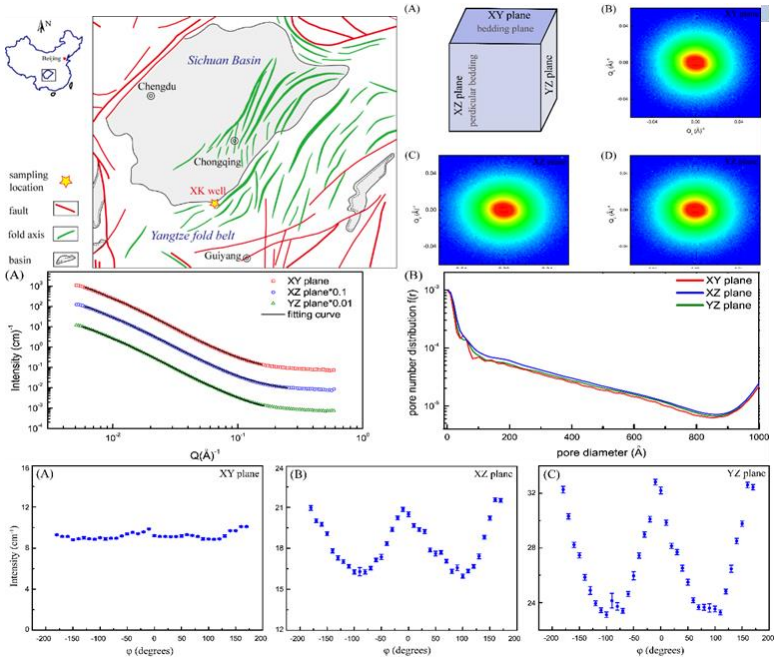


CCS Chem. 2021, 3, 1328–1340

Small Angle Neutron Scattering (SANS)

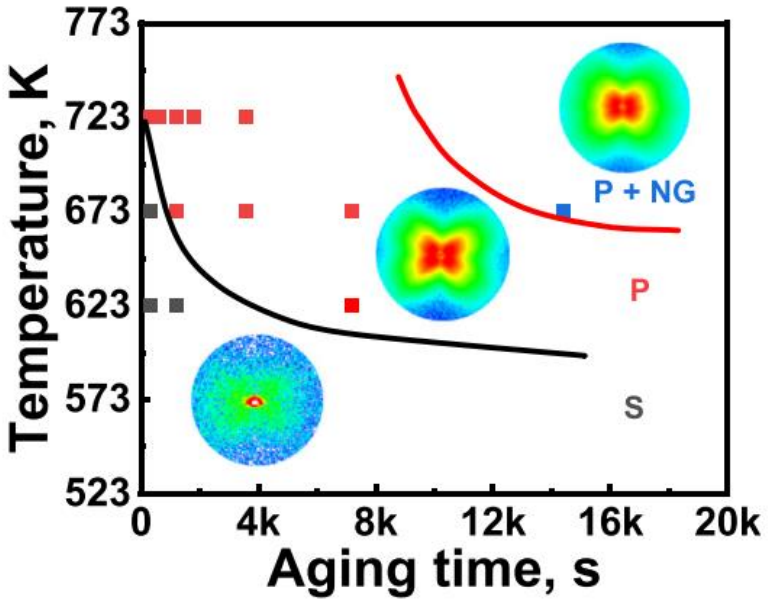
➢ ***新能源***

页岩气/油样品中纳米孔隙尺寸和取向



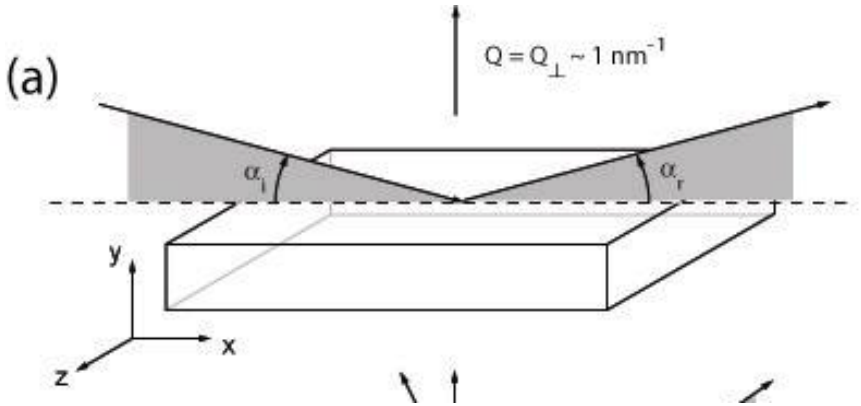
Yu Wang,et al., Energy & Fuels, 34(2020): 7974-7984

➢ TiNb合金中的两种调幅分解的微观相分离形态



Acta Materialia 233 (2022) 117969

Reflectometer (CSNS)





以磁性薄膜为主，采用垂直样品几何，其主要应用领域有：

1) 各类自旋电子材料的膜层结构及磁结构分析；

2) 氧化物材料的界面结构及磁性分析；

3) 超导及拓扑材料薄膜的结构分析；

4) 软物质薄膜的膜层结构分析。

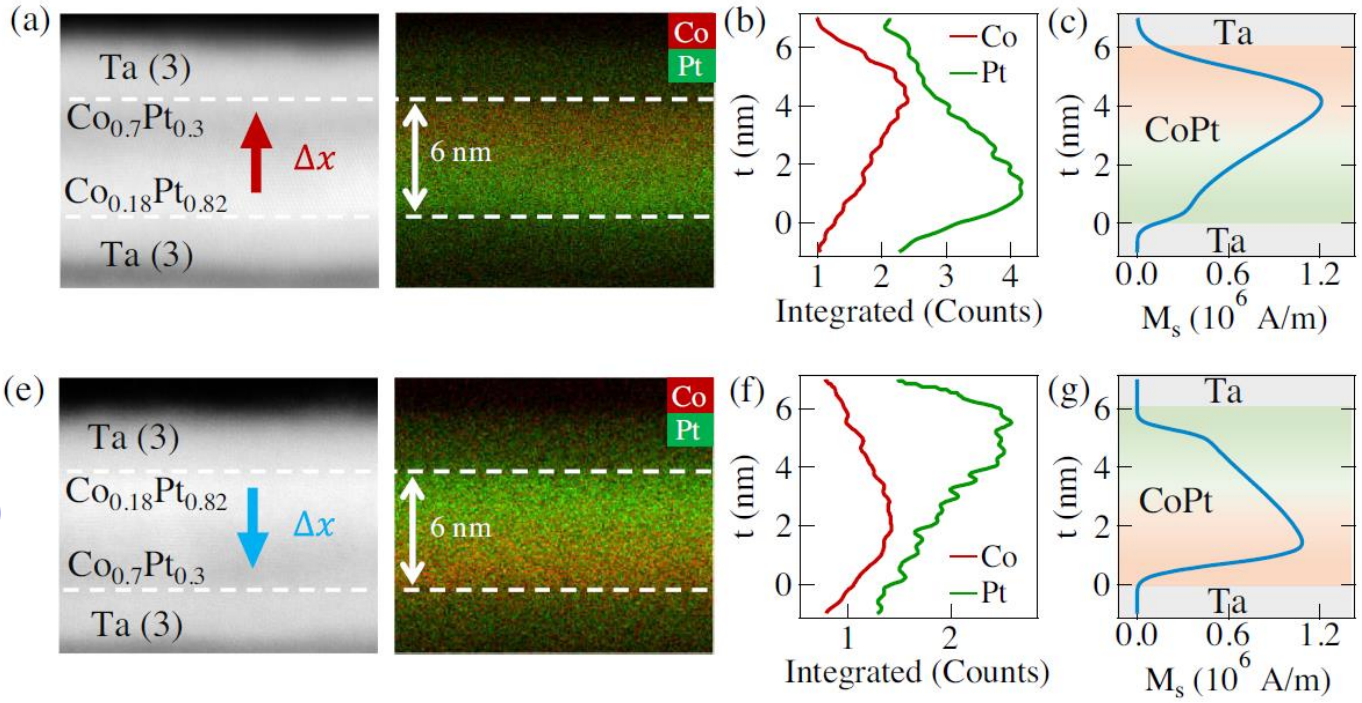
Reflectometer (CSNS)

PNR是唯一可以精确测量铁磁薄膜内部磁性分布的方法。

TEM得到的成分变化　　**PNR实测的磁性变化**

Quantifying the Dzyaloshinskii-Moriya Interaction Induced by the Bulk Magnetic Asymmetry

清华大学　江万军等
Phys. Rev. Lett. **128**, 167202 (2022)

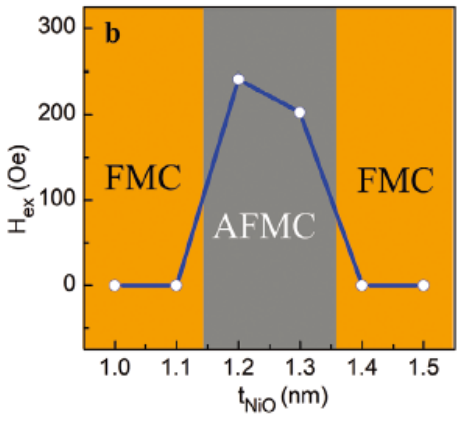


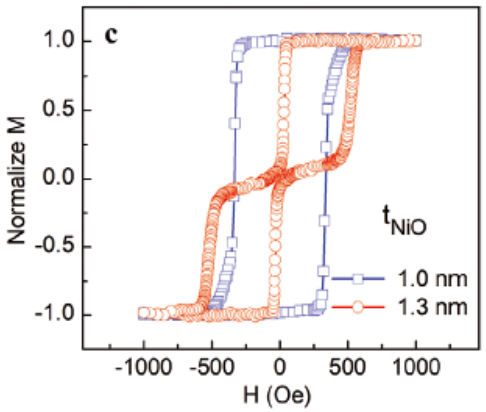
Reflectometer (CSNS)

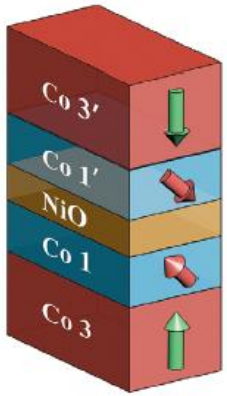
Magnetic Skyrmions in a Hall Balance with Interfacial Canted Magnetizations

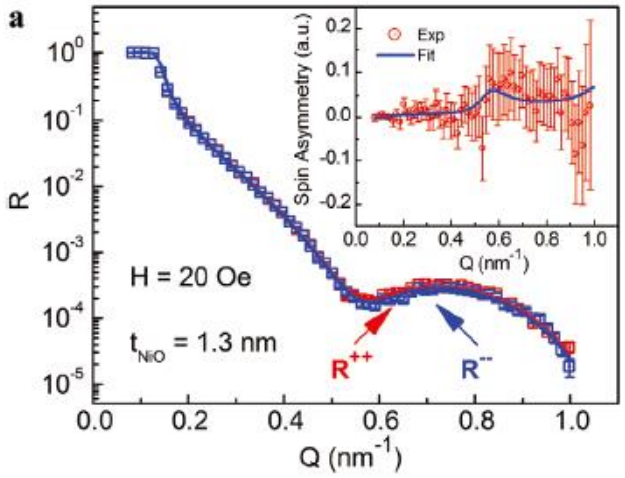
北科大 王守国等，
Adv. Mat.
32, 1907452 (2020).

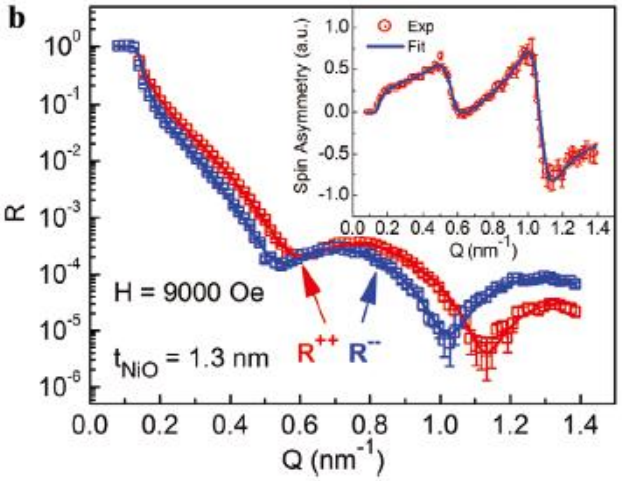
通过PNR明确了NiO导致的倾斜磁性，从而进一步导致其磁性斯格明子的产生。



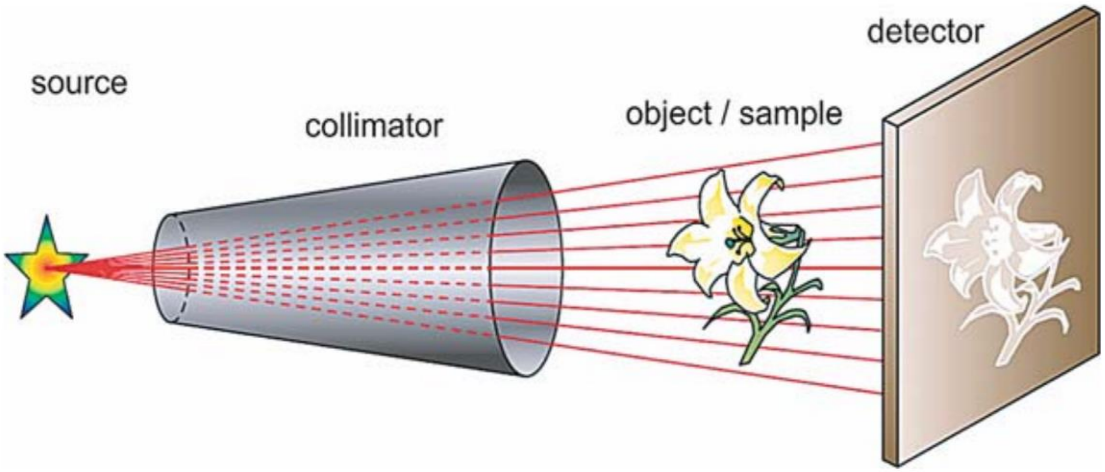


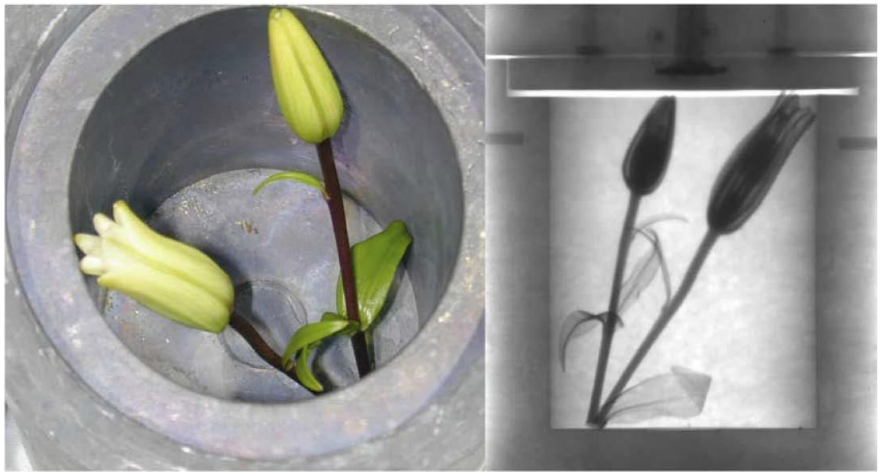






Neutron Imaging

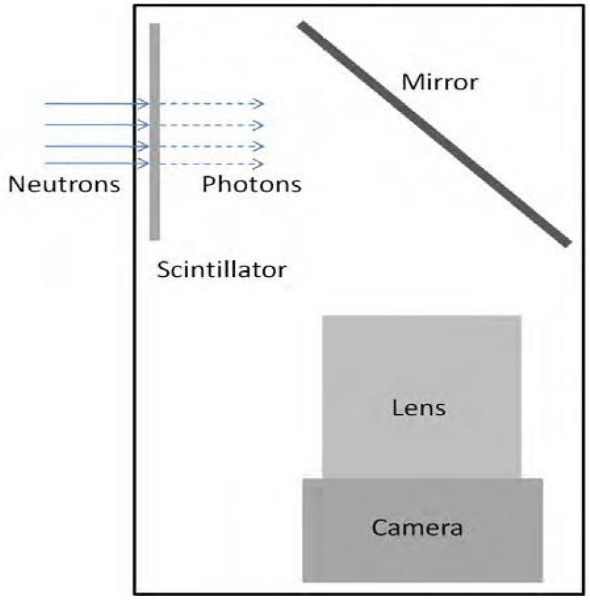




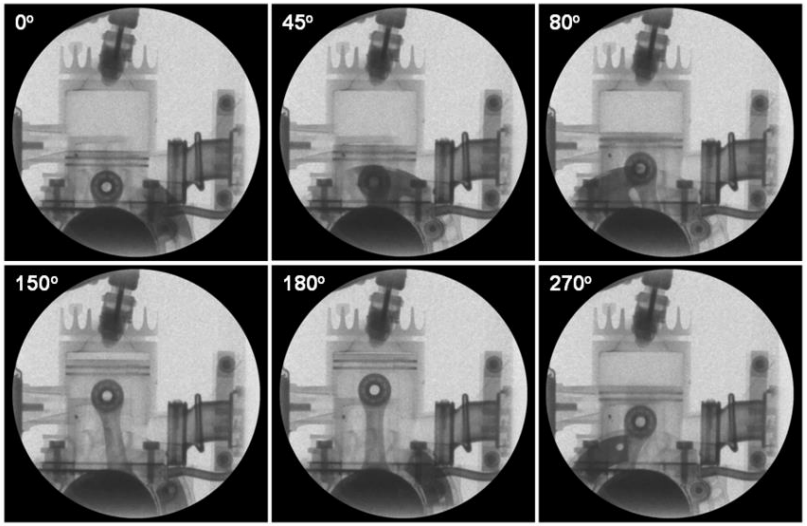




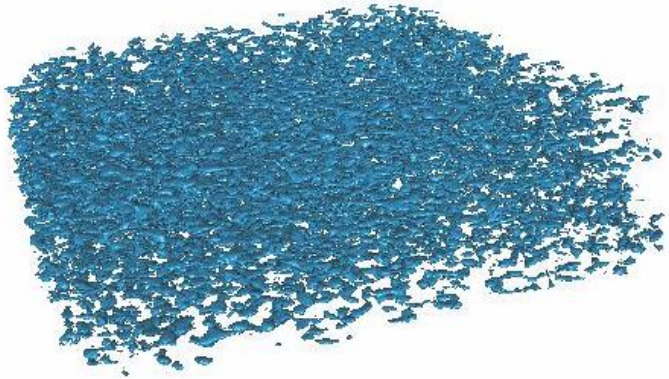
Neutron Imaging

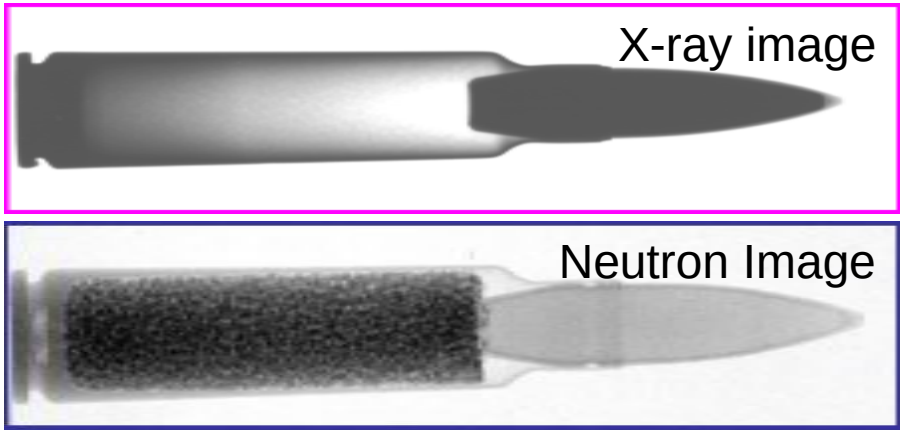




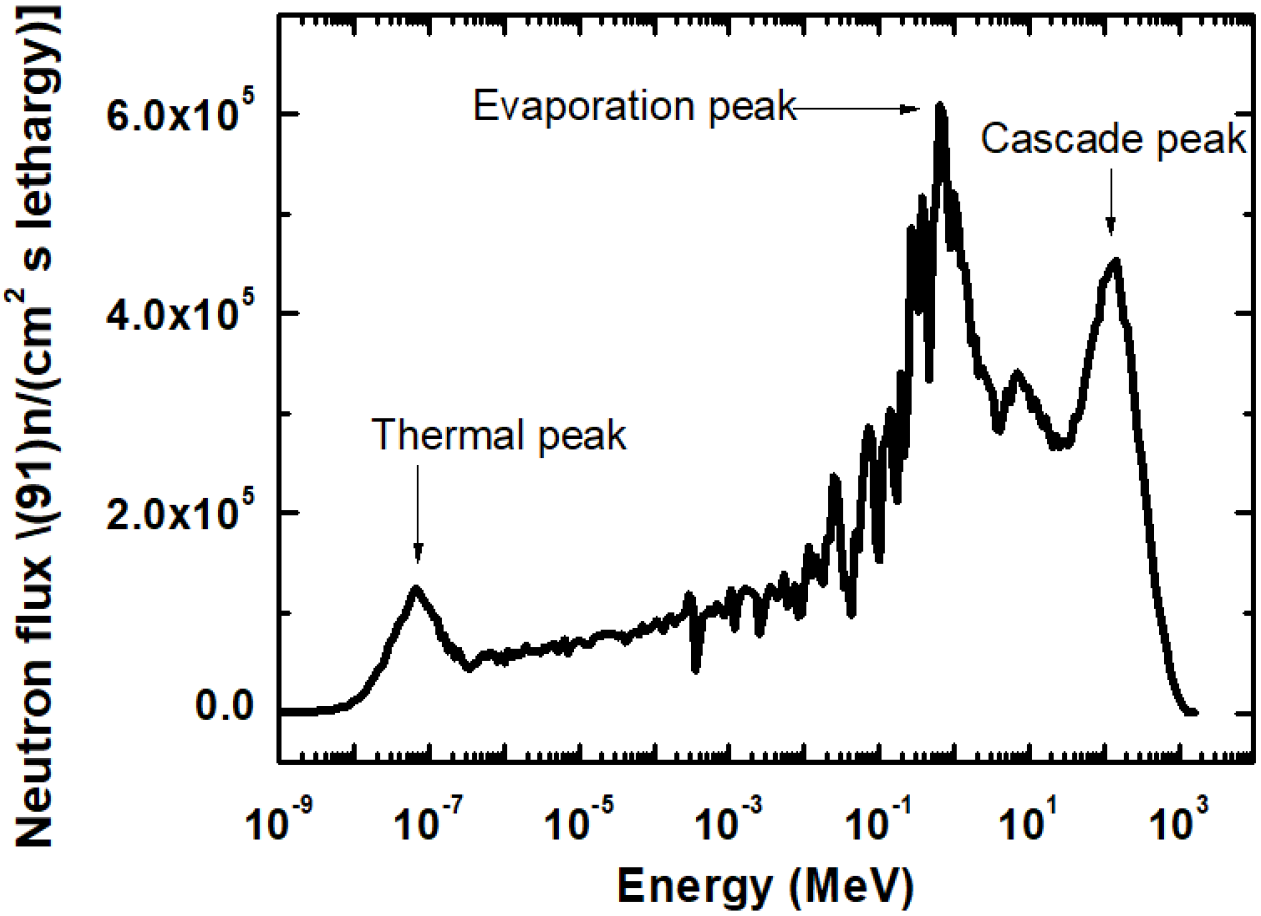


Carbon foam matrix in a Li battery (H. Bilheux and S. Voisin)

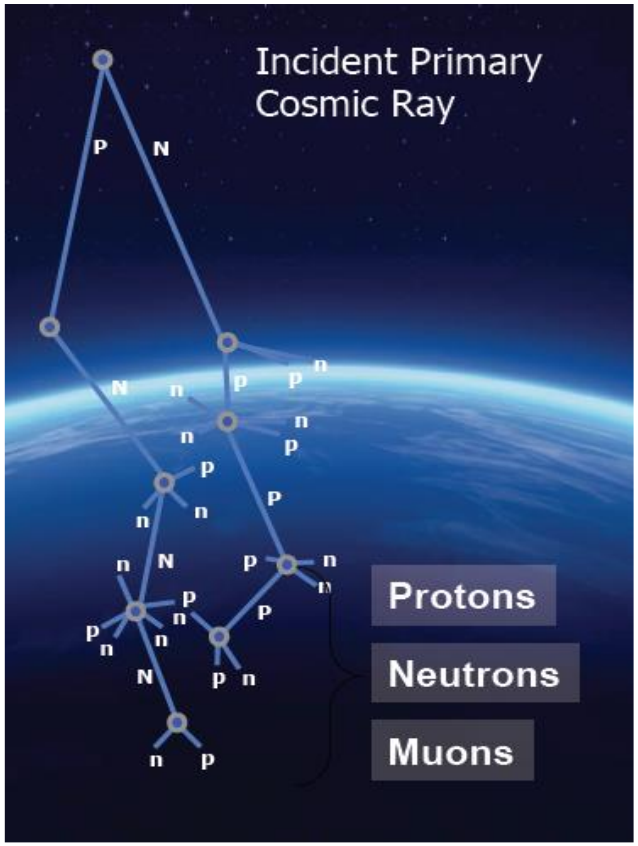


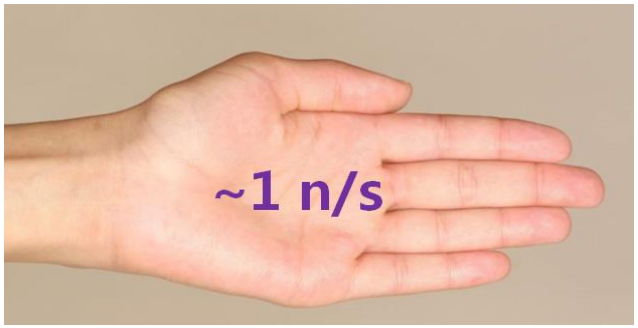


Neutron Irradiation, CSNS



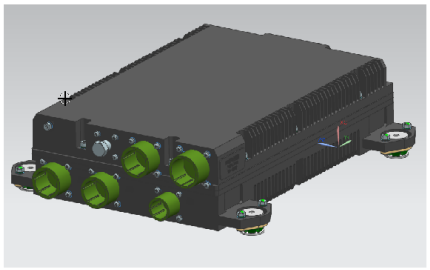
Atmospheric neutron spectrum at ANIS

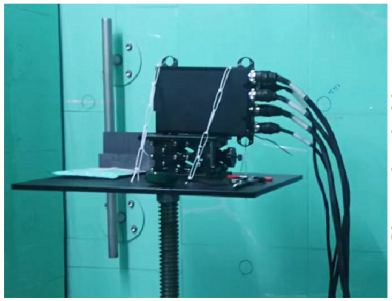


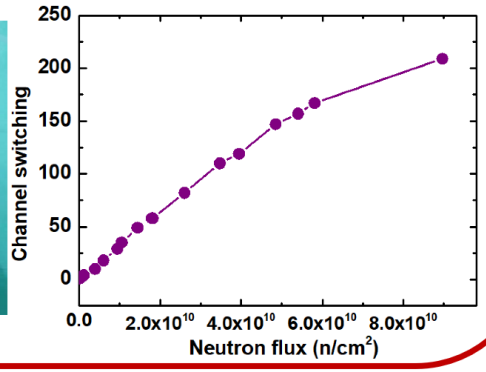


Neutron Irradiation, CSNS









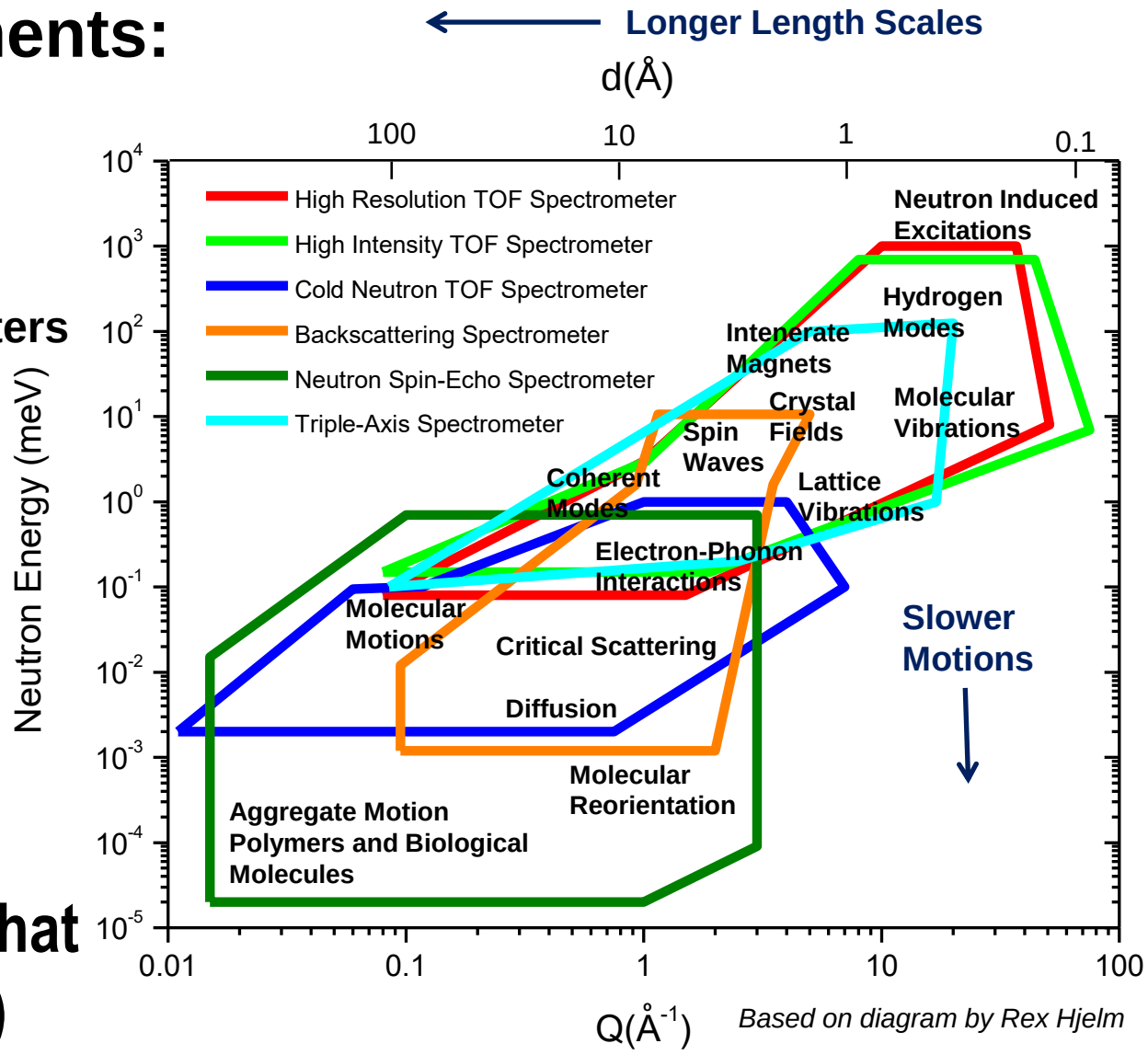
- 任务来源：航空发动机电子控制器大气辐射单粒子效应；
- 辐照试验：在中子辐照环境下，该航空电子控制器发生典型飞行剖面的通道复位与通道切换事件，试验结果符合事件数与中子注量的线性关系；
- 测试意义：试验结果为该数字电子控制器适航取证提供有利证据，现实意义重大。

面向国家重大需求，面向国民经济主战场。44

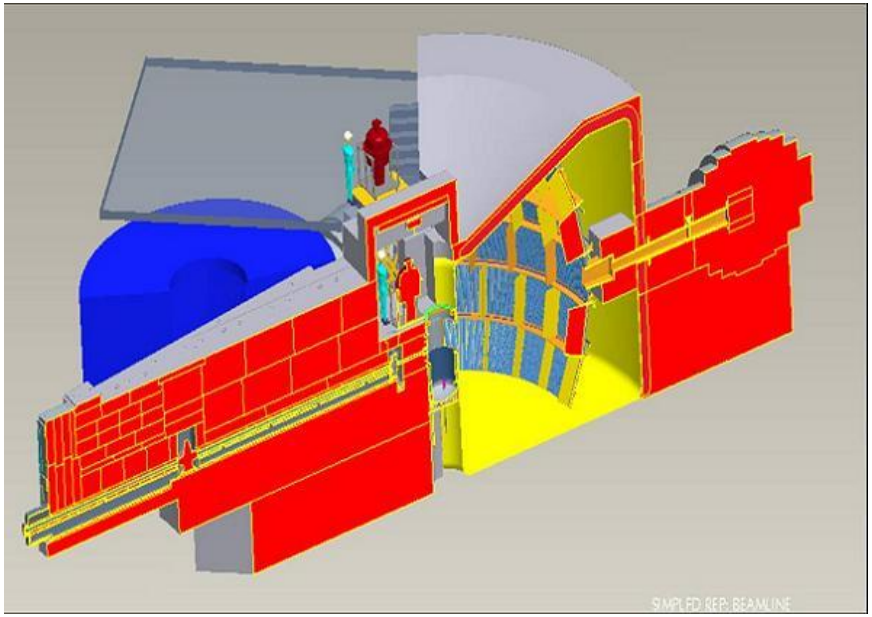
Inelastic Neutron Scattering Instruments

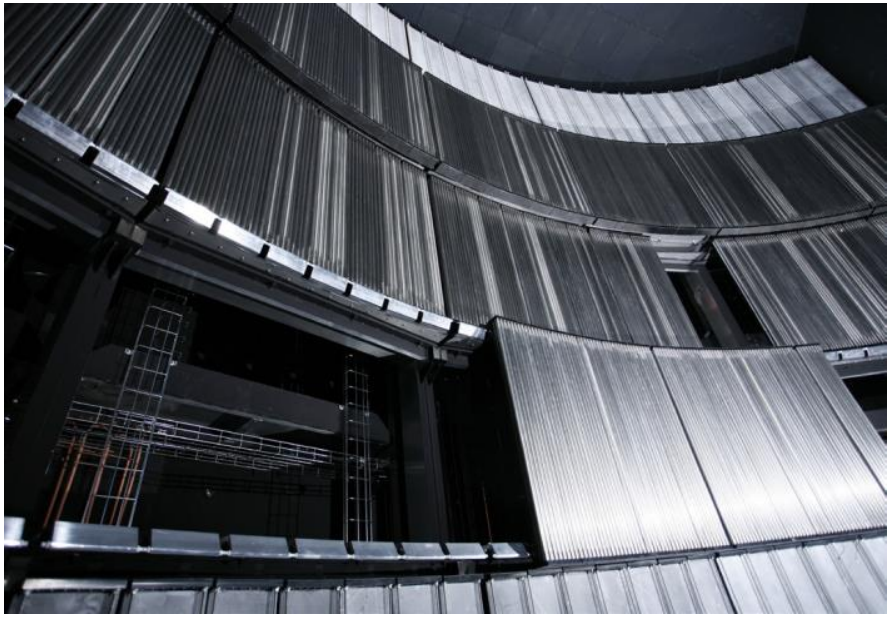
- **Inelastic instruments:**
  - Direct Geometry TOF Spectrometers
  - Indirect Geometry TOF Spectrometers
  - Triple-Axis Spectrometers
  - Backscattering Spectrometers
  - Neutron Spin-Echo Spectrometers

- **Used to study dynamics such as phonons, magnons, and diffusion (i.e. what the atoms are doing)**

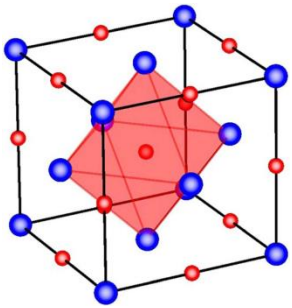


SEQUOIA: A Direct Geometry TOF Spectrometer at the SNS

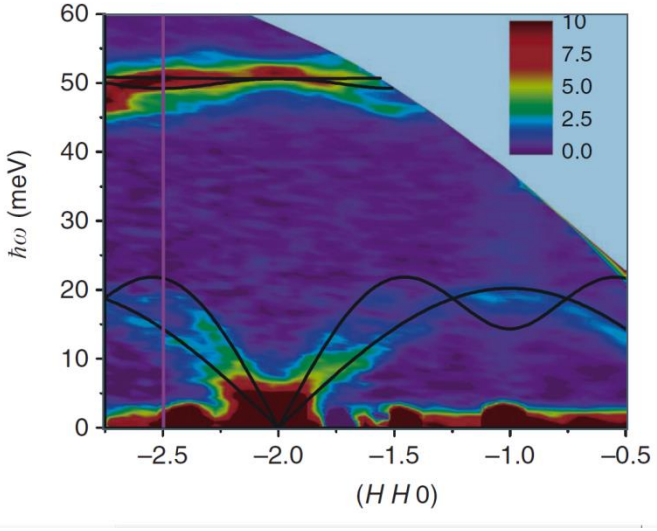


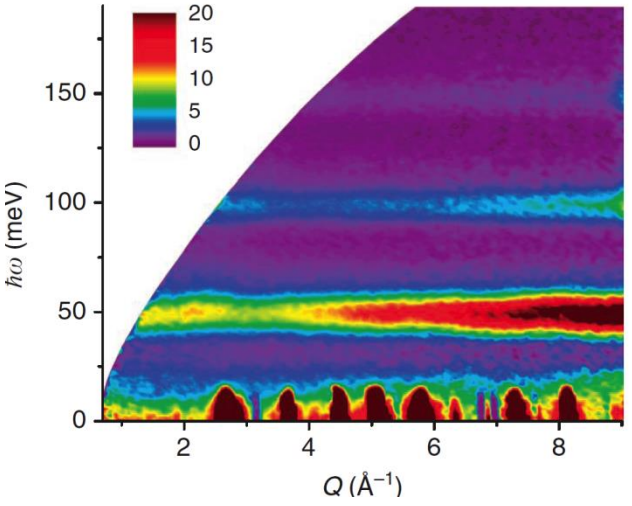


Quantum oscillations of nitrogen atoms in uranium nitride



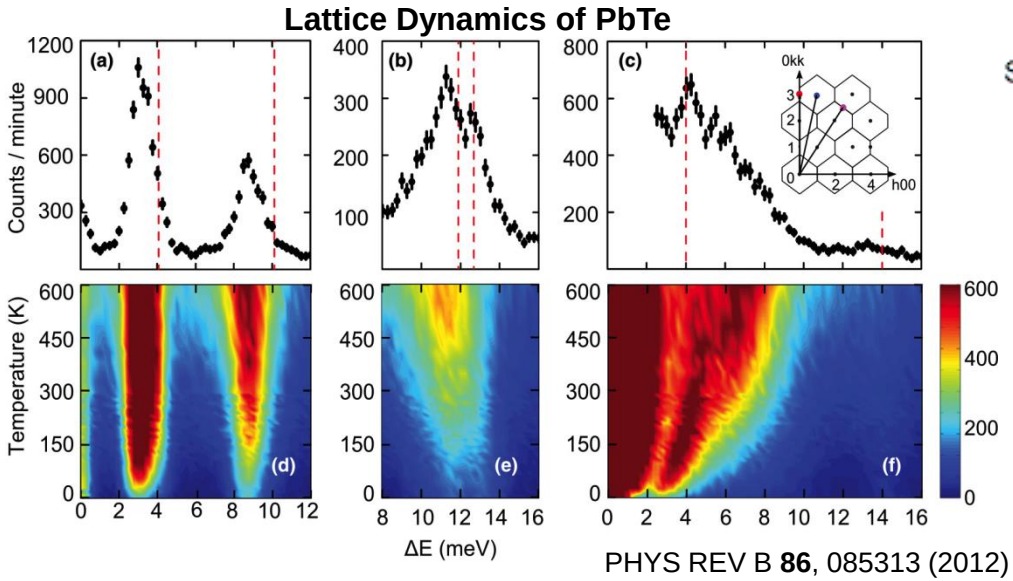
Nature Communications v**3**, p1124 (2012)



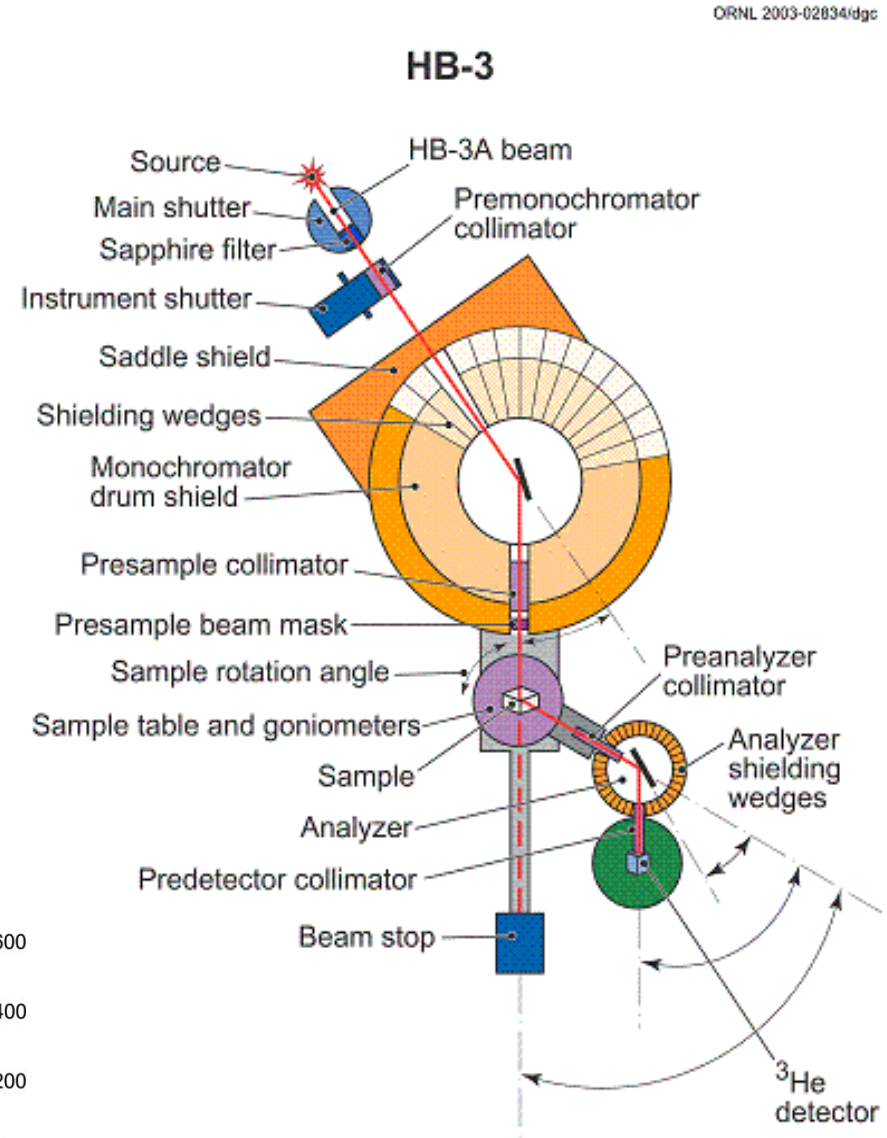


Triple-Axis Spectrometer

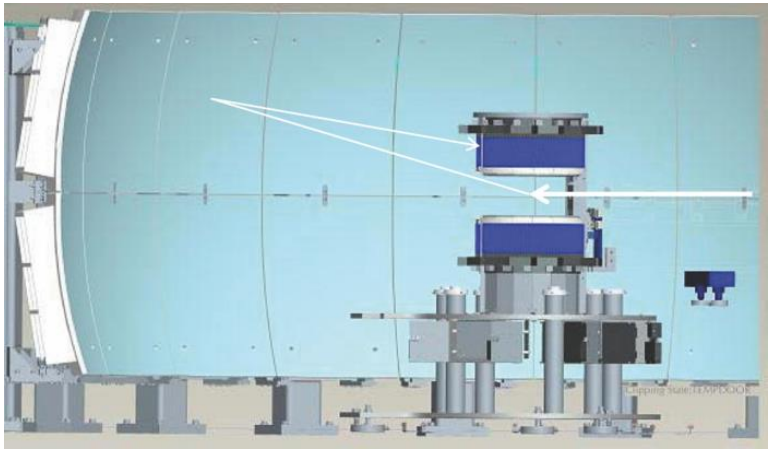




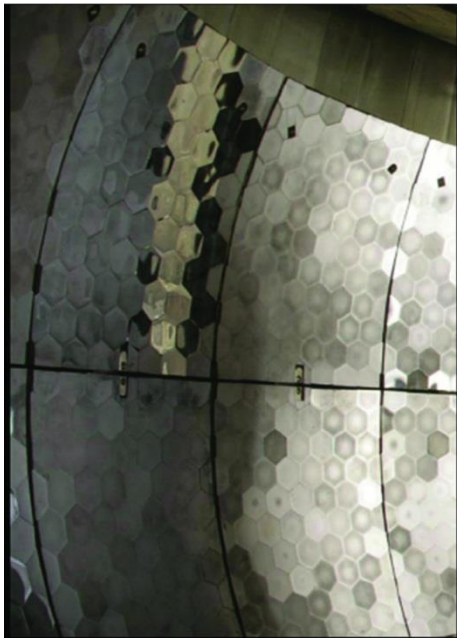
PHYS REV B **86**, 085313 (2012)



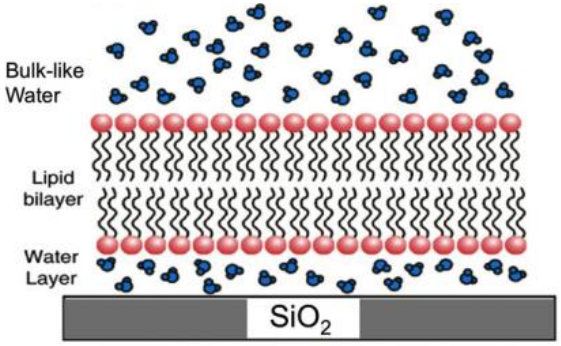
BASIS: An Inverted Geometry Backscattering Spectrometer

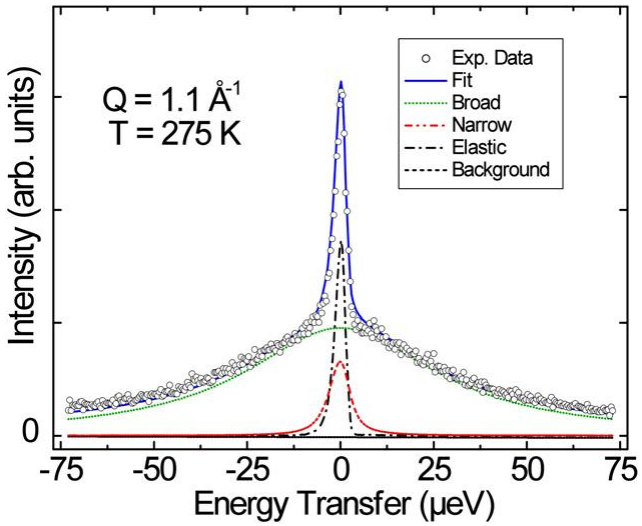




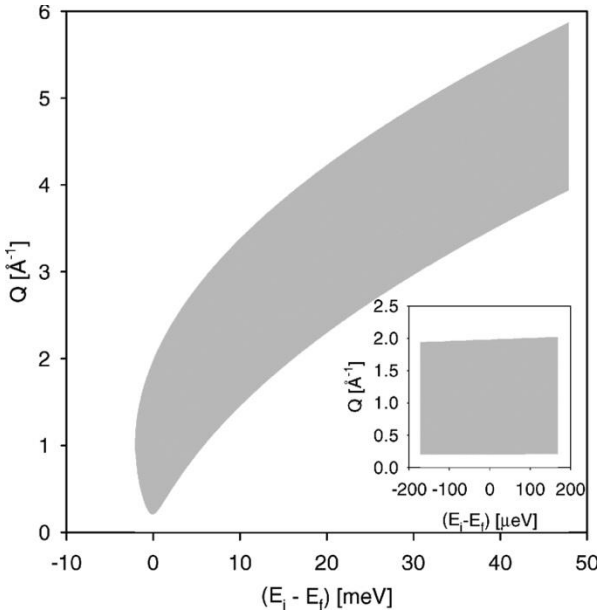


Study of water diffusion on single-supported bilayer lipid membranes by QENS



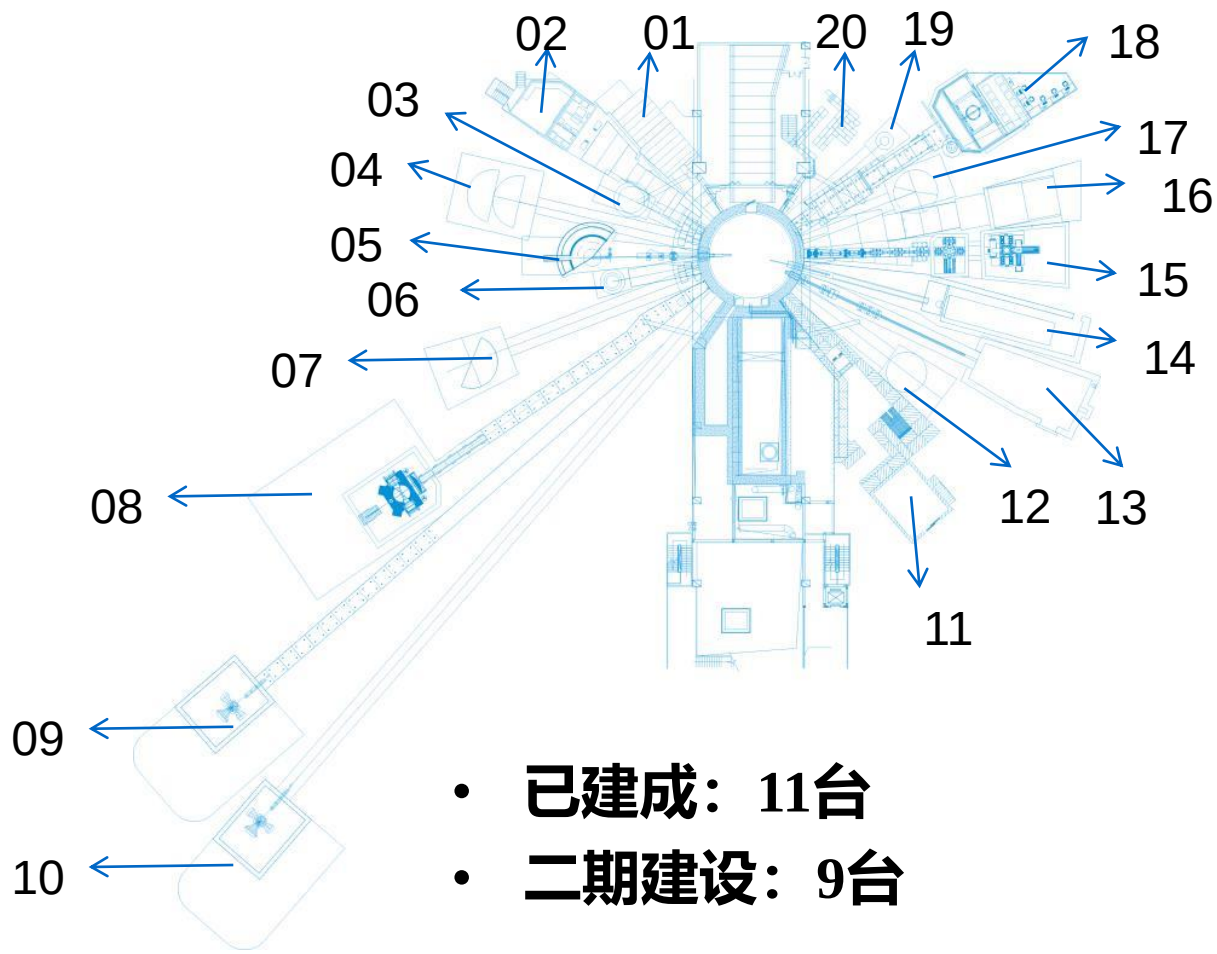


Bai M., *EPL* **98**, 48006 (2012)



The China Spallation Neutron Source，instruments

CSNS谱仪规划图



- **已建成：11台**
- **二期建设：9台**

01 小角中子散射仪
02 多功能反射仪
03 液体反射仪
04 冷中子直接几何非弹谱仪
05 高能直接几何非弹谱仪
06 逆几何分子振动谱仪
07 预留
08A 工程材料中子衍射仪
08B 测试线站
09 高分辨中子粉末衍射仪
10 中子背散射谱仪
11 大气中子辐射谱仪
12 中子物理与应用谱仪
13 能量分辨成像谱仪
14 微小角中子散射谱仪
15 高压中子衍射谱仪
16 多物理谱仪
17 弹性漫散射中子谱仪
18 通用粉末衍射仪
19 大分子单晶中子衍射仪
20 极化非弹谱仪

高能直接几何非弹性中子散射飞行时间谱仪

法人单位：中山大学

共建单位：散裂中子源科学中心

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提案类型：
1.直接申请
2.快速申请

Neutron instrumentation

- **Instrument design is driven by the needs of the scientific community coupled with the source capabilities along with advances in neutron optics and detectors.**
- **In the near term instrument development will be primarily focused on:**
  - **Focusing optics**
  - **Polarization**
  - **Detectors**
  - **Instrument development infrastructure (computer simulations)**
  - **New techniques and applications**

“If the neutron had not been discovered by Chadwick in 1932, it would have been invented.” --Brockhouse

References

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Dover Publications
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Neutron Scattering: A Non-Destructive Microscope for Seeing Inside Matter
by Roger Pynn
Available on-line at http://www.springerlink.com/content/978-0-387-09415-1

Polarized Neutrons
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