PSI Master School 2017

Introducing photons, neutrons and muons for materials characterization

Lecture 5: Neutron Sources and Neutron Properties

History of photons and neutrons

- Discovery of X-ray (Röntgen, 1901)
- X-ray diffraction (Laue 1914, Bragg & Bragg 1915)
- Electron diffraction (Davisson & Germer, 1927)
- Discovery of Neutrons (Chadwick, 1932)
- Neutron scattering (various, 1940-1950)

History of Neutron Sources

- Various natural sources from the decay of radioisotopes
  mostly used for particle physics experiments
  but: natural sources have low flux
- 1942 first chain reaction by Fermi
- 1945 first neutron reactors are used for neutron scattering
- 1977 first spallation neutron source

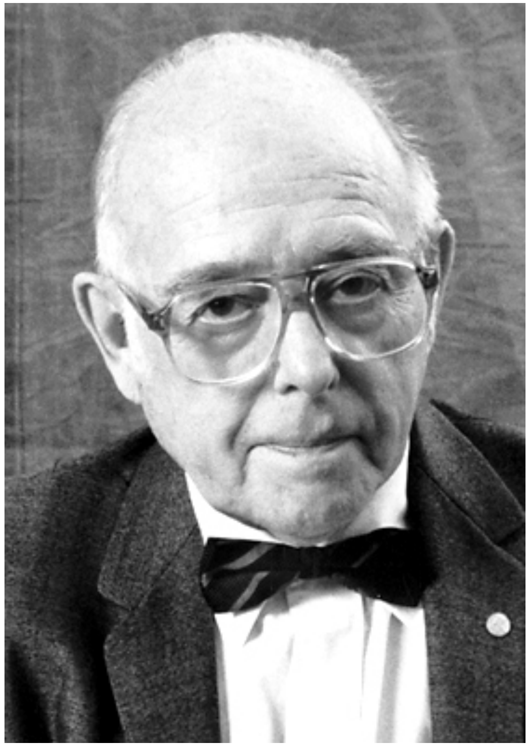
Properties of Neutrons

- $m = 1.675\ 10^{-24}$ g
- No charge
- S=1/2
- magnetic moment $\mu_n = -1.913\ \mu_k$ ($\mu_k = e\hbar/2M_pc$)
- unstable ($T_{1/2}$ = 855.5 s):

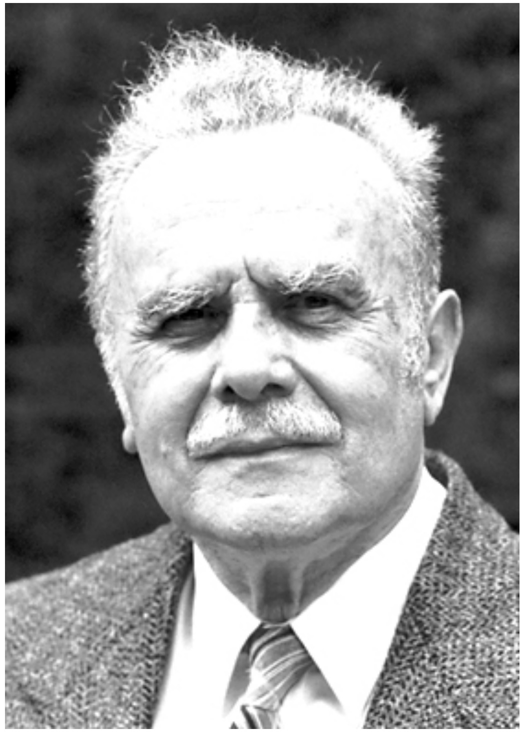
  $n \rightarrow p^+ + e^- + \nu_e$ (main decay channel)

- neutron beams are difficult to control because of a lack of charge
- Excellent probe for materials because of very interaction

1994 Nobel Prize for neutron scattering



Clifford G. Shull



Bertram N. Brockhouse

"for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter" jointly with one half to Bertram N. Brockhouse *"for the development of neutron spectroscopy"* and with one half to Clifford G. Shull *"for the development of the neutron diffraction technique"*.

Natural Neutron Sources

(alpha,n) sources: neutrons are produced when alpha particles impinge on some low atomic weight isotropes

${}_4Be^9 + {}_2He^4 \rightarrow {}_6C^{12} + n + 5.7\ MeV$
Po-alpha decay ($T_{1/2} \sim 140d$) or Ra-alpha decay ($T_{1/2} \sim 1690\ y$)

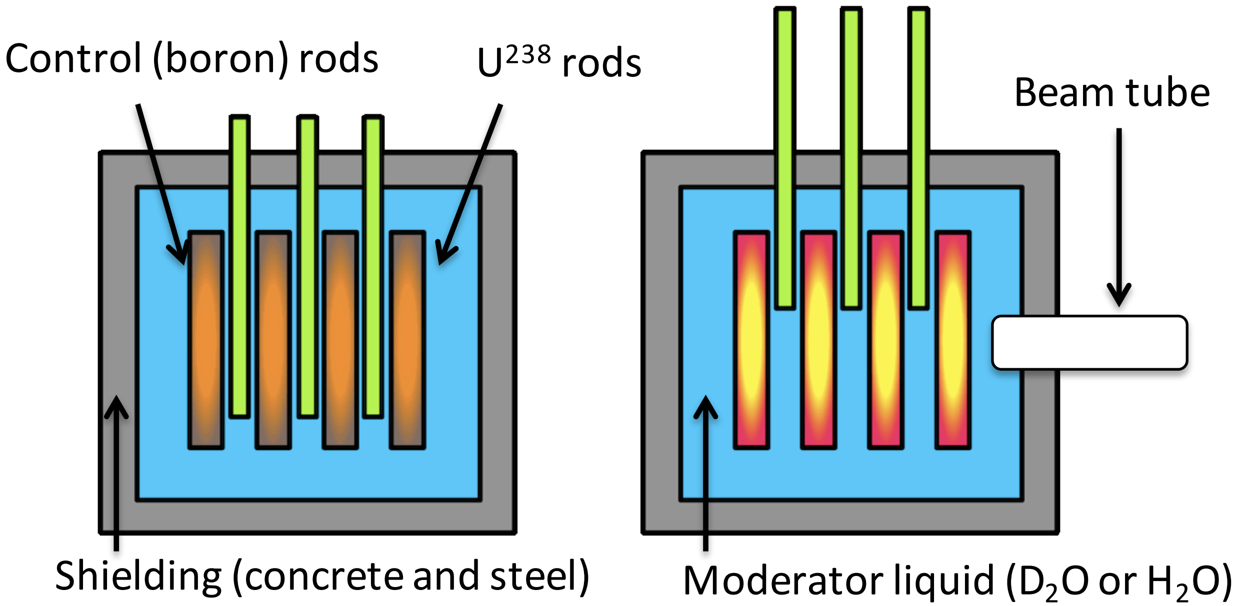
Neutron yield: $2 \cdot 10^7$ n/s

(gamma,n) sources: neutrons are produced when high energy photons hit nuclei (gamma energy > neutron binding energy)

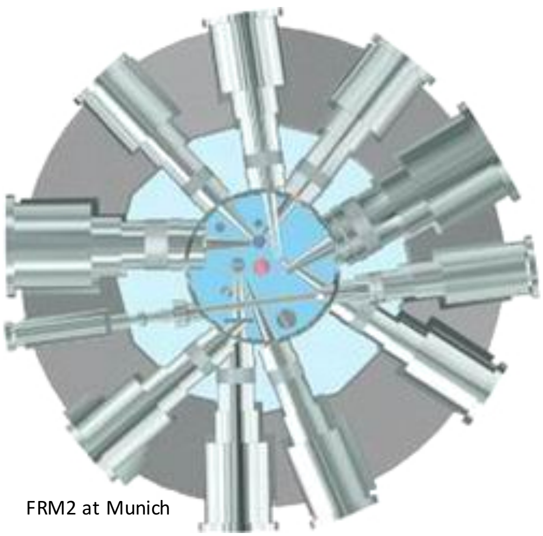
H_2 and Be_9: lowest binding energy (2.2 and 1.7 MeV)
Na^{24} with 2.76 MeV

Neutron yield: $3 \cdot 10^6$ n/s

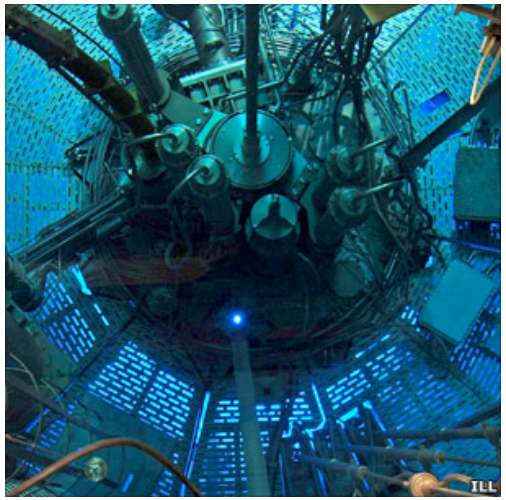
Neutron production at reactors



Adapted from stanford.edu



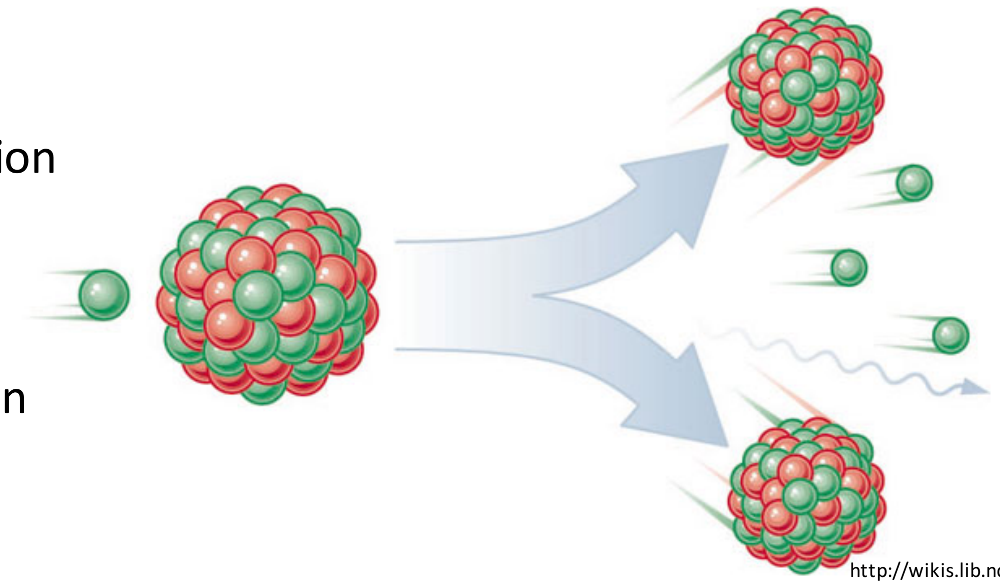
FRM2 at Munich



bbc.co.uk

Neutrons from fission

- Neutron induced neutron generation
- Average neutron yield:
  thermal fission of U^{235}: 2.5n
  fast fission of U^{238}: 2.6n
  spontaneous fission of U^{238}: 2.4n



http://wikis.lib.ncsu.edu

- Fission process of U^{235}

$$U^{235} + n_{th} \rightarrow \left(U^{236}\right)^* \overset{i.e.}{\rightarrow} \left(I^{139}\right)^* + \left(Y^{96}\right)^* + n$$

$$\left(I^{139}\right)^* \overset{2.7\,s}{\rightarrow} \left(I^{138}\right)^* + n \overset{5.9\,s}{\rightarrow} \left(Xe^{138}\right)^* + \beta^- \overset{17\,m}{\rightarrow} \left(Cs^{138}\right)^* + \beta^- \overset{32\,m}{\rightarrow} Ba^{138} + \beta^- \text{ (stable)}$$

$$\left(Y^{96}\right)^* \rightarrow \left(Y^{95}\right)^* + n \overset{10.5\,m}{\rightarrow} \left(Zr^{95}\right)^* + \beta^- \overset{63.3\,d}{\rightarrow} \left(Nb^{95}\right)^* + \beta^- \overset{35\,d}{\rightarrow} Mo^{95} + \beta^- \text{ (stable)}$$

Exponential increase of number of neutrons

Flux up to 10^{15} n/cm^2/s

Neutron production at spallation sources

- Neutron production uses a high-energy proton beam generated in a particle accelerator
- Protons hit heavy-metal target and generate neutrons through the spallation process

Early Example: Spallation Neutron Source, Los Alamos, USA

- Linear accelerator, storage ring
- Liquid tungsten target is used

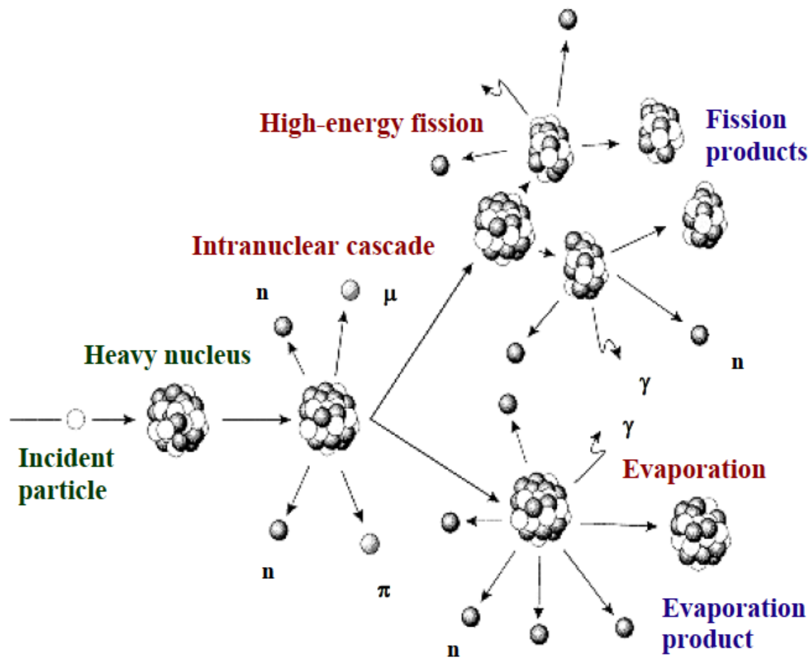
SNS spallation target, Oak Ridge

Spallation process

Spallation reaction:

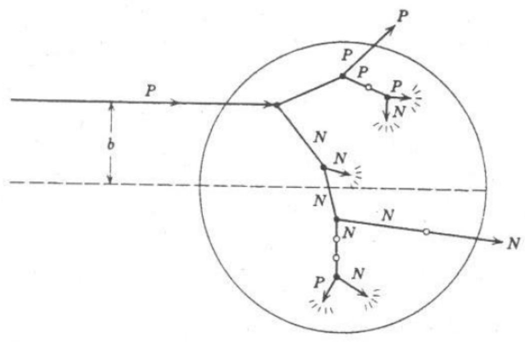
light projectile (p, n, or light nucleus) with high kinetic energy (>MeV) interacts with a heavy nucleus and causes the emission of a large number of hadrons (mostly neutrons) or fragments.

Spallation has two stages:
intra-nuclear cascade and de-excitation



Spallation reaction physics, Antonin Krasa

Intra-nuclear cascade:
Interaction with individual nuclei, hadron generation such as pions with energies > 100 MeV



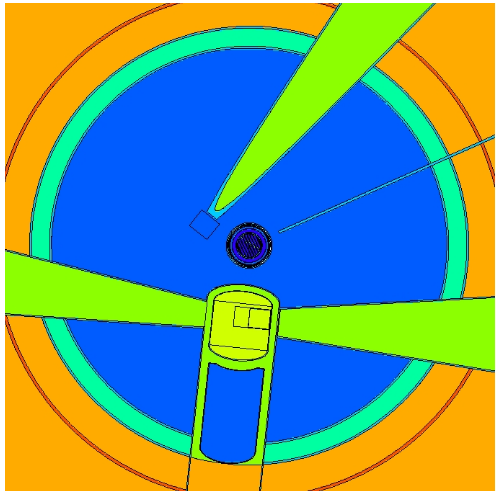
De-excitation:
Isotropic evaporation of n, d, t with energies up to 40 MeV

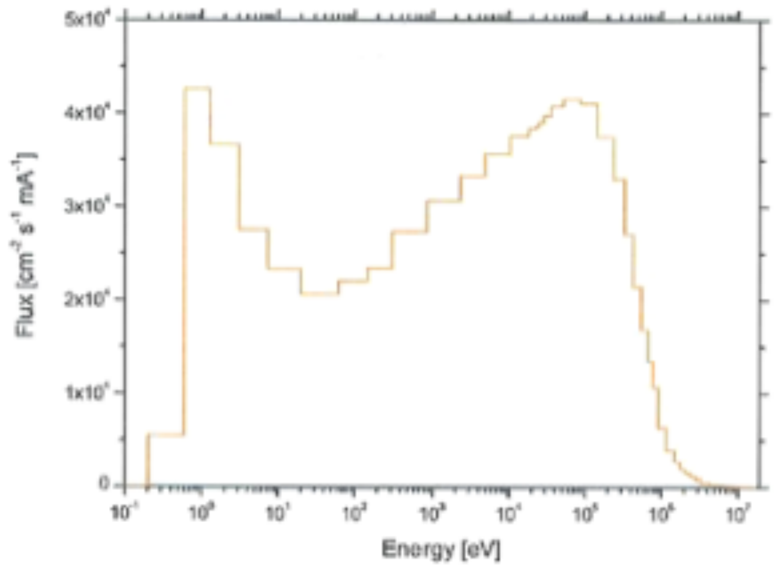
Neutron yields: ~ 10-20 neutrons per proton

Flux up to 10^{14}-10^{15} n/cm^2/s

Neutron moderators

Goal: produce neutrons with energies useful for materials physics research

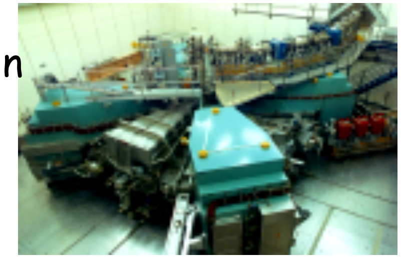


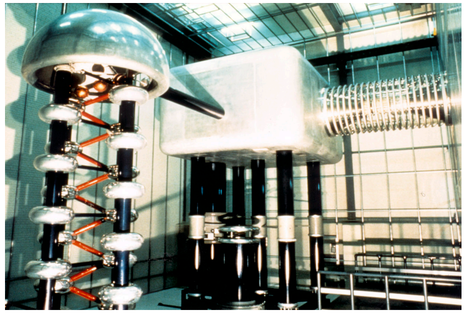


www.psi.ch

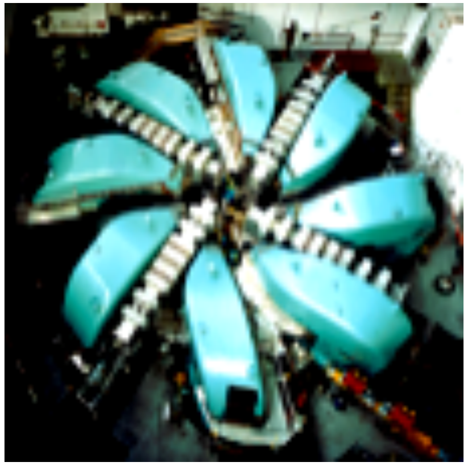
The Proton Accelerator and the Target Stations

Pre-cyclotron
72MeV

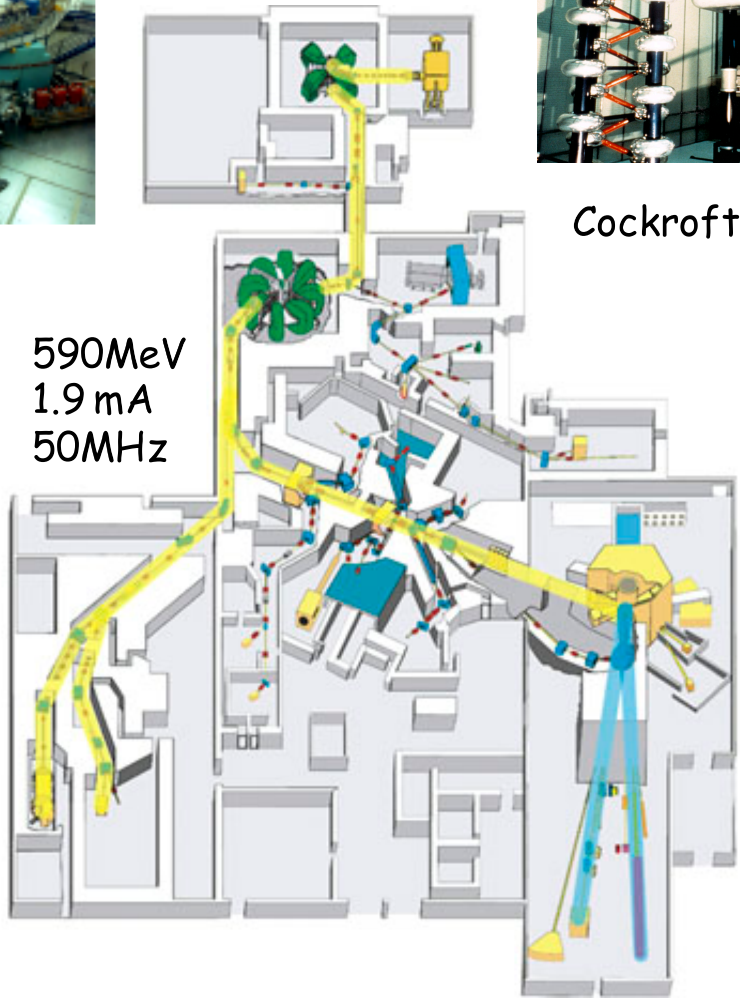




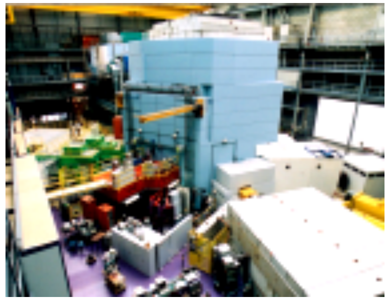
Cockroft-Walton, 12 MeV



590MeV
1.9 mA
50MHz



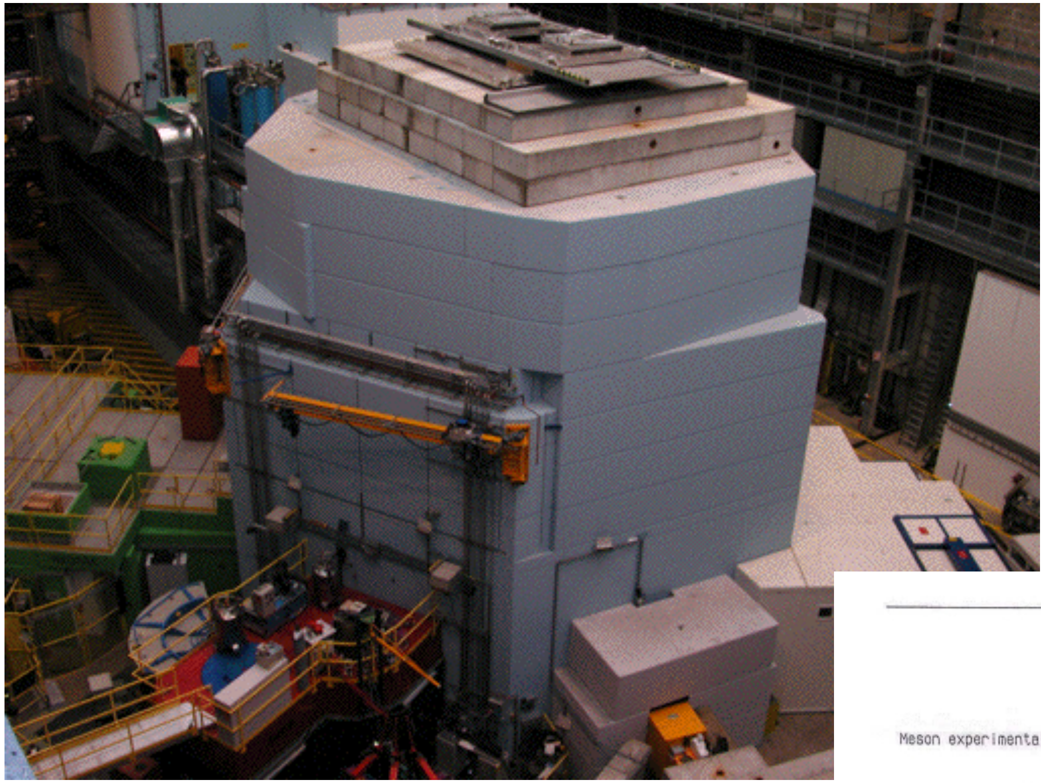
Main cyclotron 590MeV



SINQ, 590 MeV
1.2 mA on target

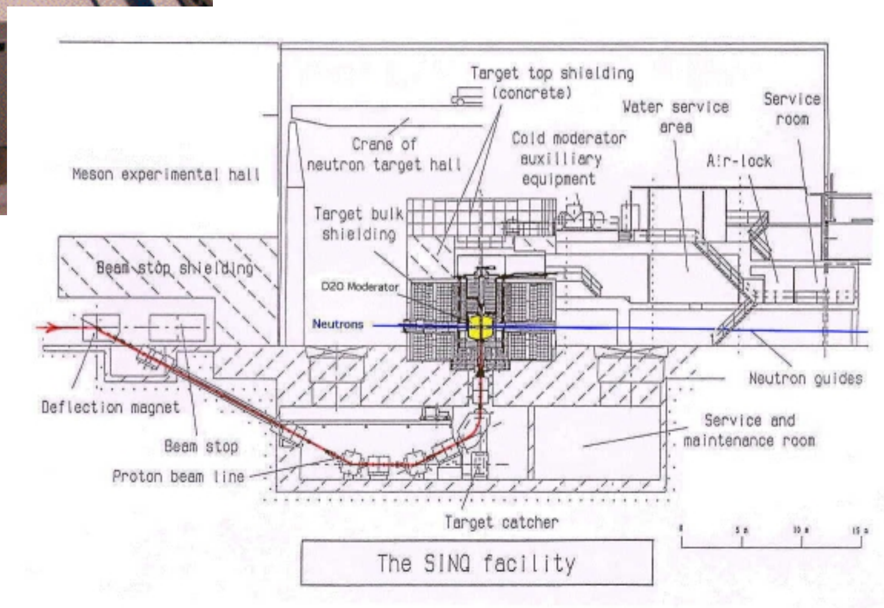
Muon Stations

SINQ spallation neutron source

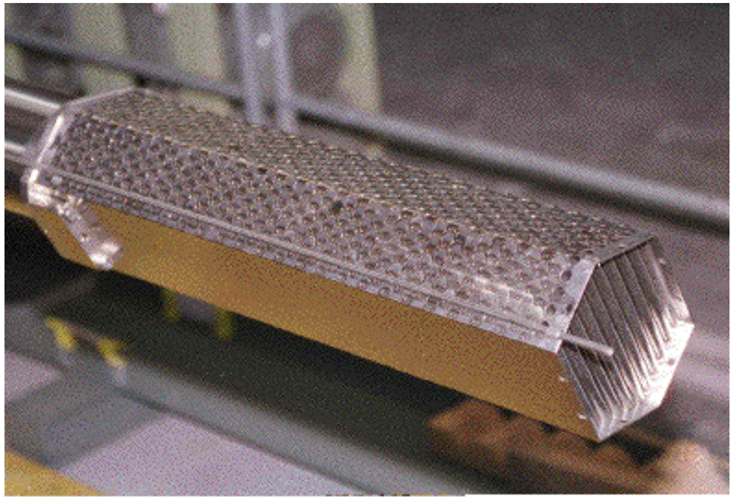


Large shielding block

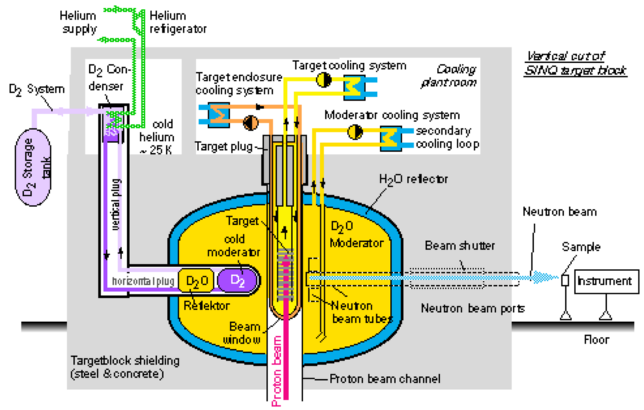
Proton beam hits target from vertically below

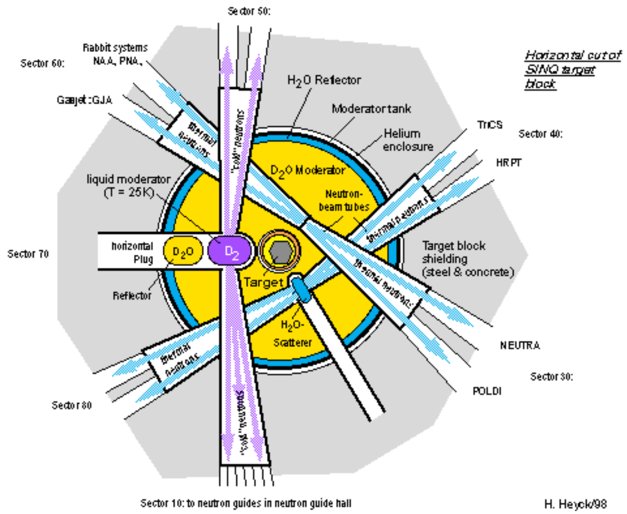


SINQ: 1 MW Continuous Spallation Source



Principle of the Spallation Neutron Source SINQ



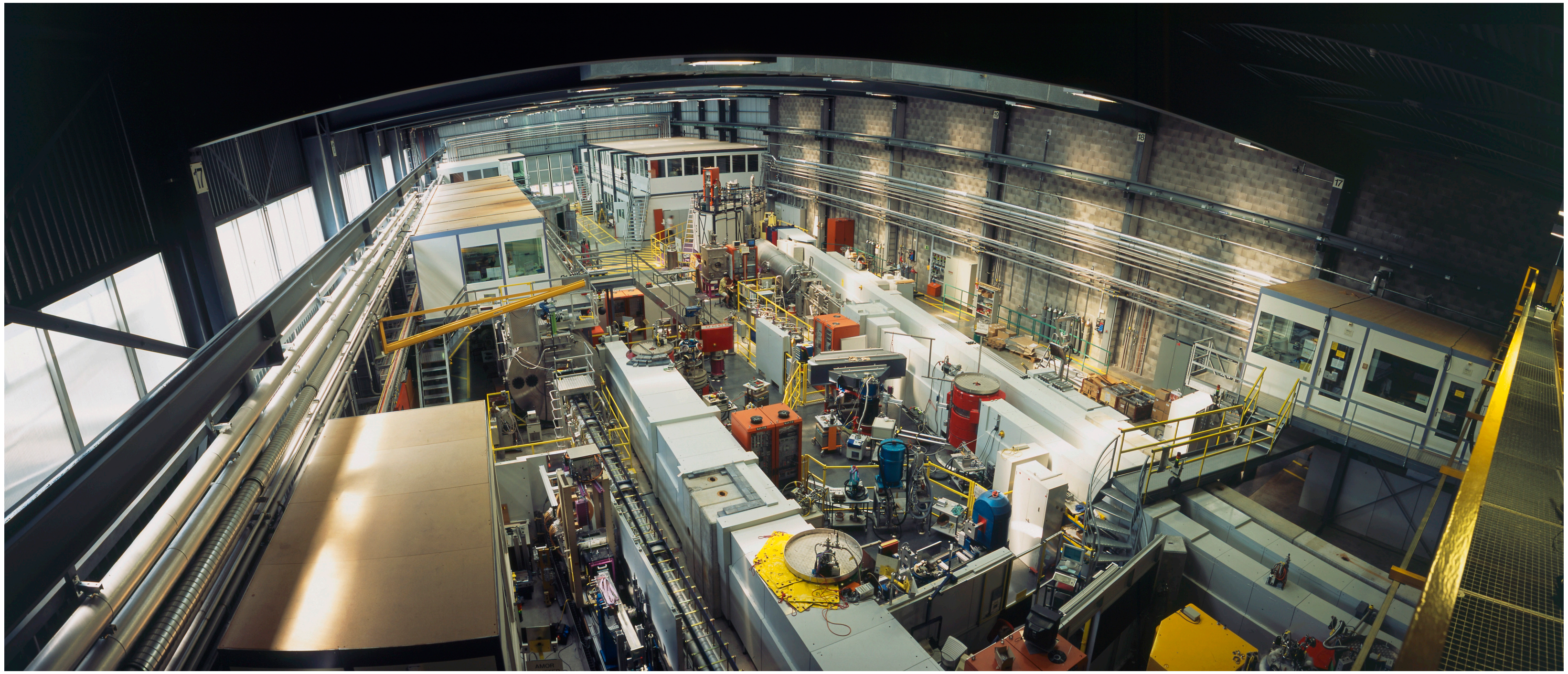


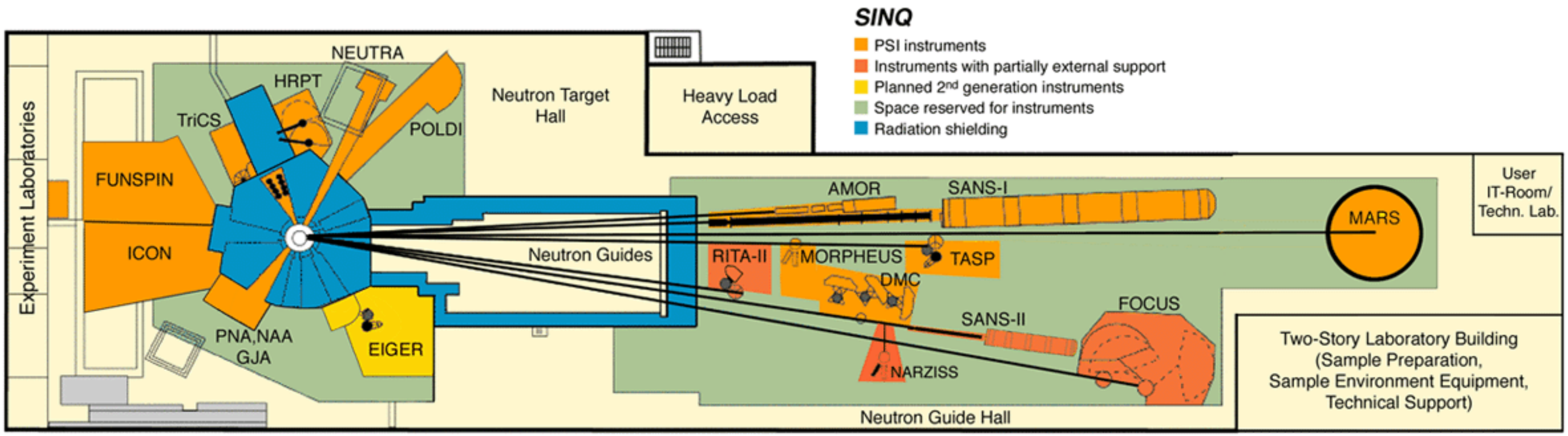
Canneloni-Target:Solid Pb-Rows
1 target per year (200 days)
storage area for 40 targets

Updates 2006:
Liquid PbBi
new cavities for cyclotron
(present flux goal: 2.6mA, max 3.5mA)
Ultra Cold Neutron Source (2nd Target-Station)

Double Walled Al-tank (D_2O/H_2O)
20 Liter cold D_2 source (35K)

Neutron instrumentation





Neutron velocity in thermal equilibrium

Maxwell distribution: $$\phi(v) \approx v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)$$

$\phi(v)$ is maximal for:

$$\frac{d\phi(v)}{v} = 0 = v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)\left[2v - v^2\left(\frac{2mv}{2k_B T}\right)\right]$$

$$\rightarrow \quad v = \sqrt{\frac{2k_B T}{m}}$$

$$\rightarrow \quad E_{kin} = \frac{1}{2}mv^2 = k_B T \qquad !!!$$

epithermal neutrons:	~ 100	-1000 meV
Thermal neutrons:	~ 10	-100 meV
Cold Neutrons:	~ 0.1	-10 meV

A few formulae

Wave-length: $\lambda = \dfrac{h}{mv}$

Momentum: $k = \dfrac{2\pi}{\lambda}$

$$E = k_B T = \frac{1}{2} m v^2 = \frac{h^2}{2m\lambda^2} = \frac{\hbar^2 k^2}{2m}$$

$$E = 0.08617\ T = 5.227\ v^2 = \frac{81.81}{\lambda^2} = 2.072\ k^2$$

T=293 K : E=25.3 meV, λ=1.798 Å, v=2.2 km/s

Advantages of cold and thermal neutron scattering

- Neutron wave-length is similar to atomic distances in solids
- Neutron energies is similar to that of phonons and many magnetic excitations
- Neutrons penetrate deep into materials: measurement of bulk properties is possible
- Neutron magnetic moment allows an interaction with magnetic degrees of freedom
- Overall weak interaction with matter: materials do not get destructed during the measurement process

Neutron Guides

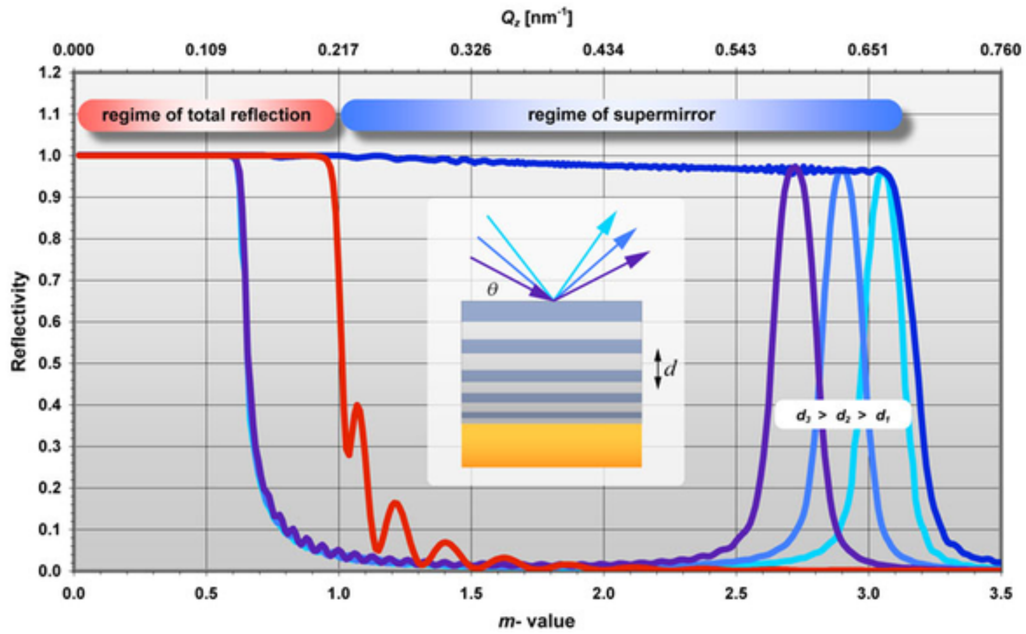
- Neutrons can not be guided with electric/magnetic fields
- Neutron can be guided through reflecting mirrors via total reflection

- Total reflection: $\frac{4\pi \sin(\theta)}{\lambda} < q_c$

- q_c depends on material
  for Ni: q_c=0.0217 Å^{-1}

- Critical angle can be made artificially larger by superlattice Bragg reflections

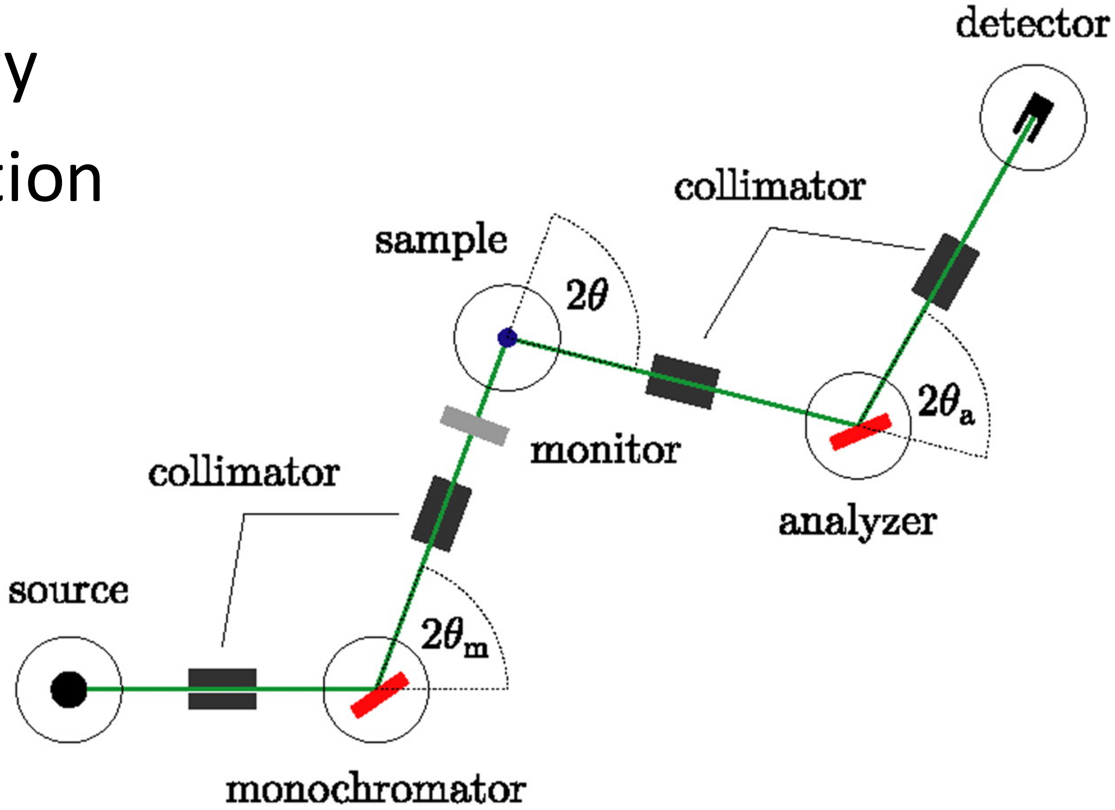
- Often used are Ni/Ti superlattices



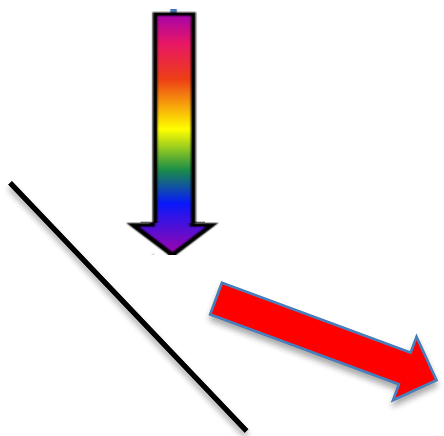
www.swissneutronics.ch

Typical neutron experiment

- Defined incident energy
- Defined incident direction
- Defined final energy
- Defined final direction
- Intensity counter
- Polarization



Monochromators

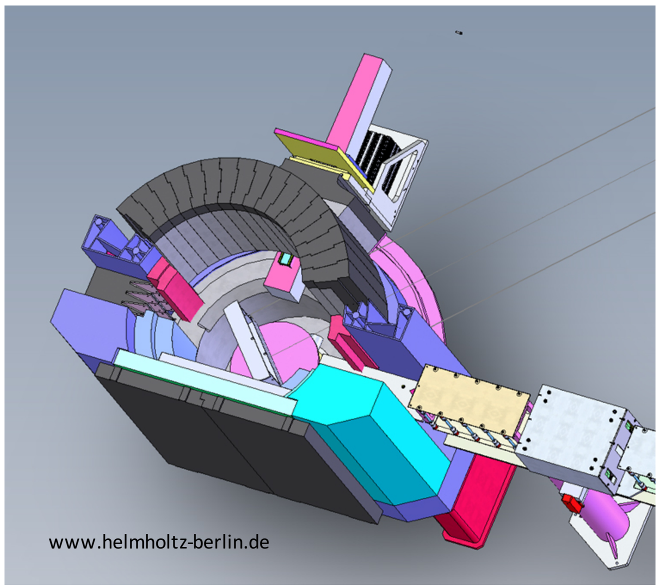


Bragg's law

$$Q = 2k_i \sin\Theta$$

$$\lambda = 2d \sin\Theta$$

One wave-length is Bragg reflected



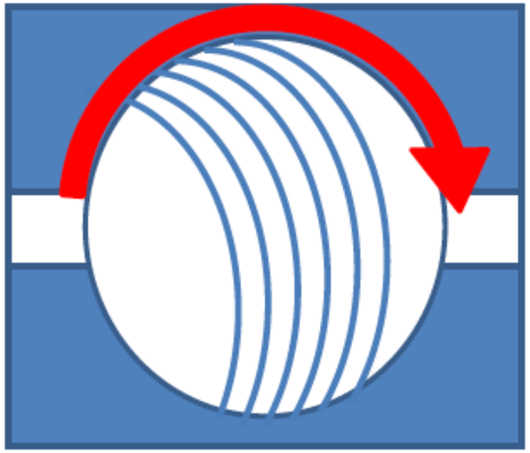
Material	Structure	Lattice parameter a (Å)	Lattice parameter c (Å)	(hkl)	F/v_0 (10^{11} cm^{-2})	G_{hkl} (Å^{-1})	$\sigma_{inc}/\sigma_{scat}$ (%)
Beryllium	hcp	2.2854	3.5807	(002)	0.962	3.5095	0.02
				(110)	0.962	5.4985	
Iron	bcc	2.86645		(110)	0.802	3.1000	3.4
Zinc	hcp	2.6589	4.9349	(002)	0.376	2.5464	1.9
PG[a]	layer	2.4612	6.7079	(002)	0.734	1.8734	0.02
				(004)	0.734	3.7467	
Niobium	bcc	3.3008		(200)	0.392	3.8071	0.04
Nickel (^{58}Ni)	fcc	3.52394		(220)	1.316	5.0431	0
Copper	fcc	3.61509		(220)	0.653	4.9159	6.8
Aluminum	fcc	4.04964		(220)	0.208	4.3884	0.55
Lead	fcc	4.9505		(220)	0.310	3.5898	0.03
Silicon	diamond	5.43072		(111)	0.147	2.0039	0.2
				(220)	0.207	3.2724	
				(311)	0.147	3.8372	
Germanium	diamond	5.65776		(111)	0.256	1.9235	2.1
				(220)	0.362	3.1411	
				(311)	0.256	3.6832	

From: Neutron Scattering with the triple-axis spectrometer, Shirane, Shapiro & Tranquada

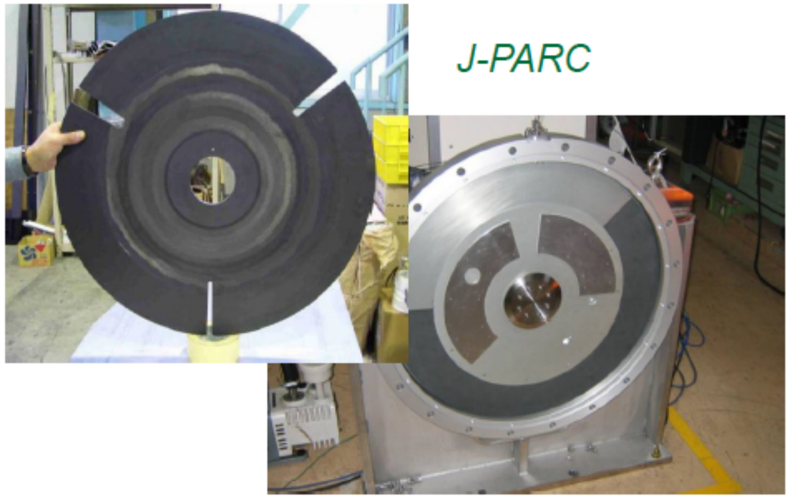
Selectors and Choppers

Neutron beams can be monochromized using choppers or velocity selectors, or they be be pulsed using disk choppers

Fermi Chopper



Disk Chopper



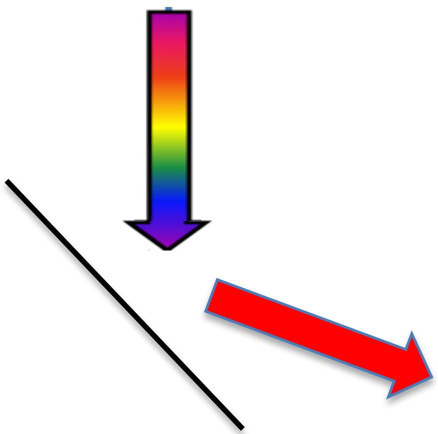
J-PARC

Velocity Selector

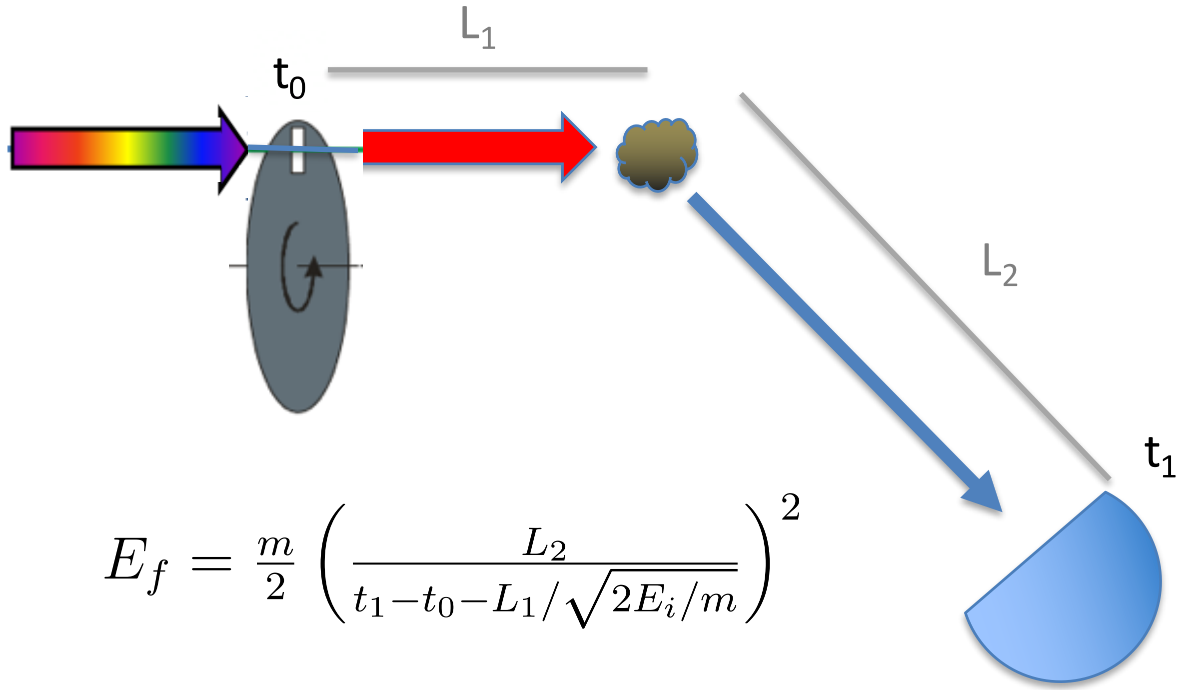
Astrium

Scattering neutron energy analysis

Analysis via Bragg reflection

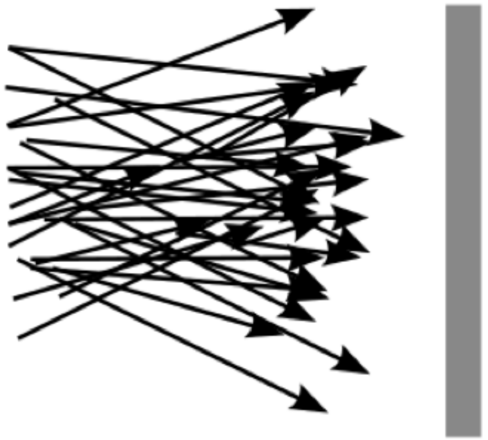


Analysis through time of flight



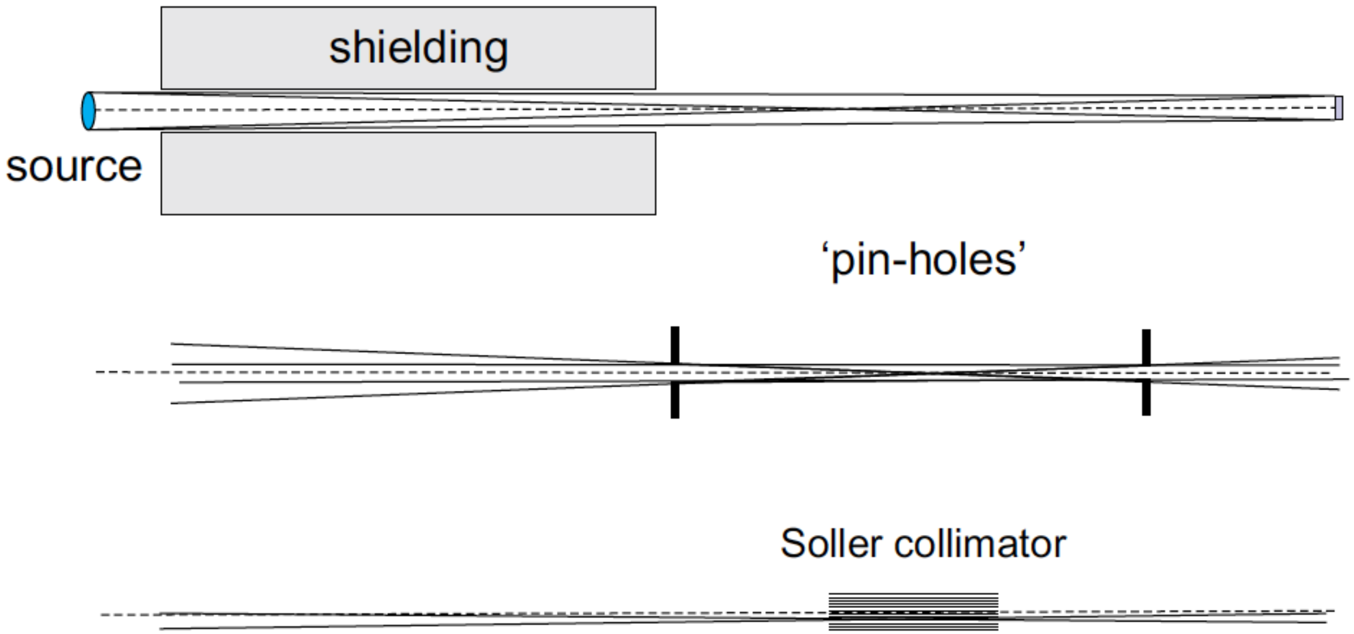
$$E_f = \frac{m}{2}\left(\frac{L_2}{t_1 - t_0 - L_1/\sqrt{2E_i/m}}\right)^2$$

Define Divergence

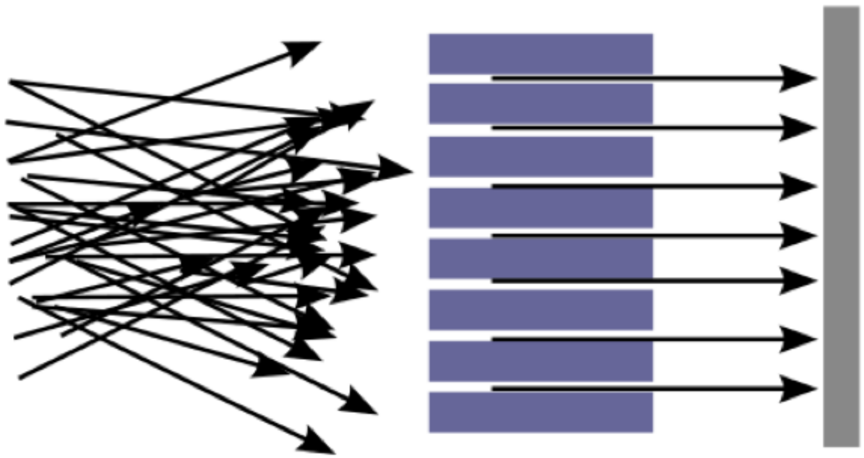


- Many experiments need a well defined divergence
- Absorb all neutron neutrons with wrong momentum

  → big intensity loss



Collimators



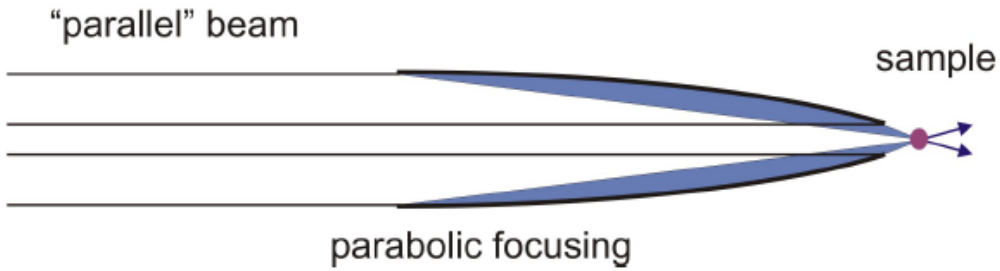
Concept: neutron with wrong direction are absorbed by walls

Collimation	
Collimation:	10'
Beam area:	40 mm (*w*) x 120 mm (*h*)
Substrate	
Material:	Mylar
Number of substrates:	64
Format of substrates:	120 mm x 200 mm
Thickness of substrates:	0.023 mm
Absorbing coating:	Gd_2O_3 printed on both sides
Frame	
Material:	aluminium
Outer cross-section:	65 mm (*w*) x 165 mm (*h*)
Length:	200 mm

Soller-type foil collimator

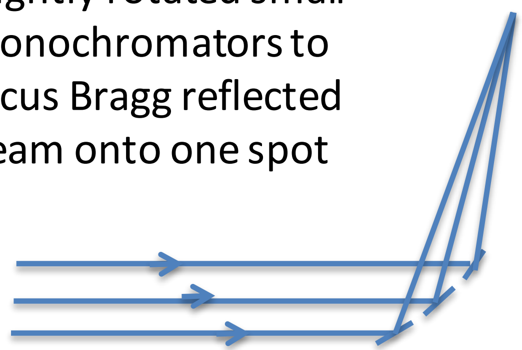
Neutron focusing

- Focusing with supermirror guides



- Focusing with curved monochromator

Slightly rotated small monochromators to focus Bragg reflected beam onto one spot



Doubly-focusing monochromator

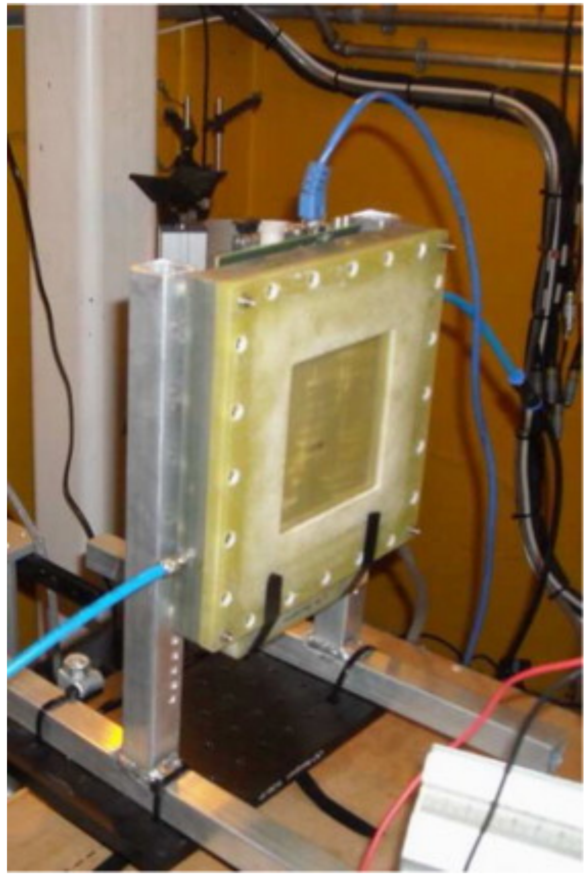
Neutron detection

- Electrically neutral particle cannot be detected directly
- Neutrons are detected via a nuclear reaction

Reaction	Isotope abundance (%)	Cross section (barn) at 1.8 Å
^{3}He(n,p)^{3}H	0.014	5330
$^{10}B(n,\alpha)^{7}$Li	19.9	3838
$^{6}Li(n,\alpha)^{3}$H	7.6	947
^{14}N(n,p)^{14}C	99.63	1.91
^{235}U(n,3n)ff	0.72	680.9

Neutron monitors

- Beam is not always stable
- Scattered neutrons have to be normalized to incoming beam
- Neutron monitors use low-pressure gas to measure incoming neutron flux without attenuating it too much
- Placed in front of samples



G. Croci et al. Nucl. Inst. Meth. **732**, 217 (2013).

Neutron detection: detectors

- High-pressure chambers
- Ideally cover as much area as possible (limited by cost)
- Most efficient are ^{3}He detectors:

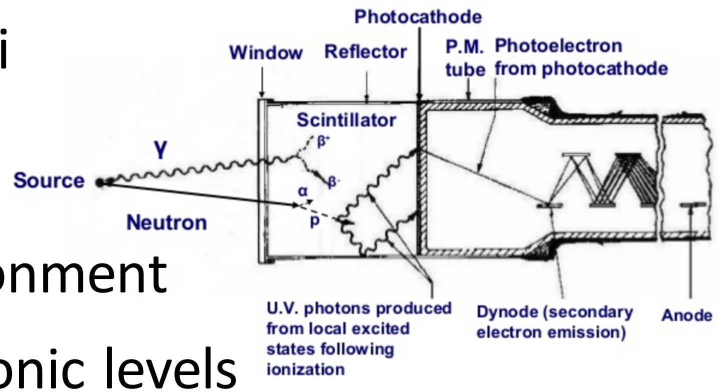
$$n + {}^3He \rightarrow {}^3H + {}^1H + 0.764\ MeV$$

- Also used: Boron detectors:

$$n + {}^{10}B \rightarrow {}^7Li^* + {}^4He \rightarrow {}^7Li + {}^4He + 0.48\ MeV\ \gamma\ +2.3\ MeV\ (93\%)$$
$$\rightarrow {}^7Li + {}^4He \qquad +2.8\ MeV\ (7\%)$$

- Alternative: Scintillation detectors using Li

$$n + {}^6Li \rightarrow {}^4He + {}^3H + 4.79\ MeV$$



- alpha particle ionizes solid state environment
- ionization leads to excitation of electronic levels
- emission of photons

How to polarize neutrons, part 1

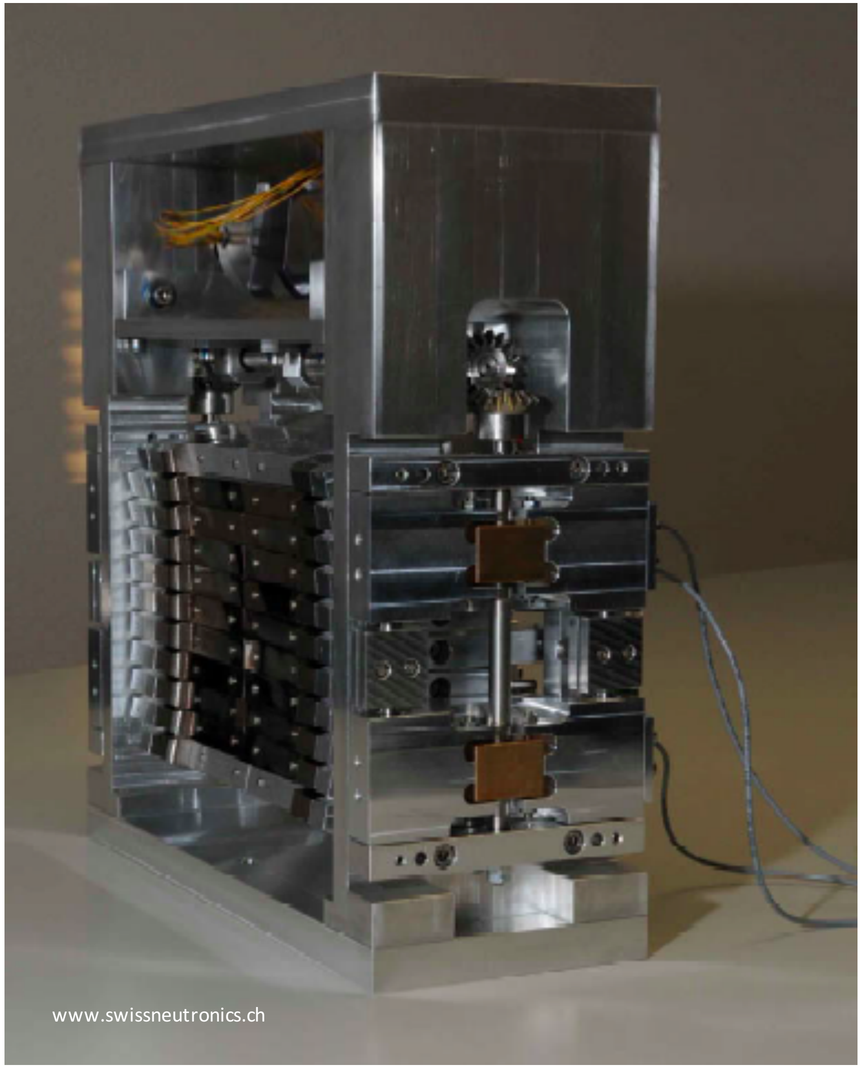
$$\left(\frac{d\sigma}{d\Omega}\right)_{u\rightarrow u} \propto (b-C)^2$$
$$\left(\frac{d\sigma}{d\Omega}\right)_{v\rightarrow v} \propto (b+C)^2$$

$$C = \frac{1}{2}\gamma r_0 g F(\boldsymbol{\tau}) \langle S \rangle$$ Magnetic scattering

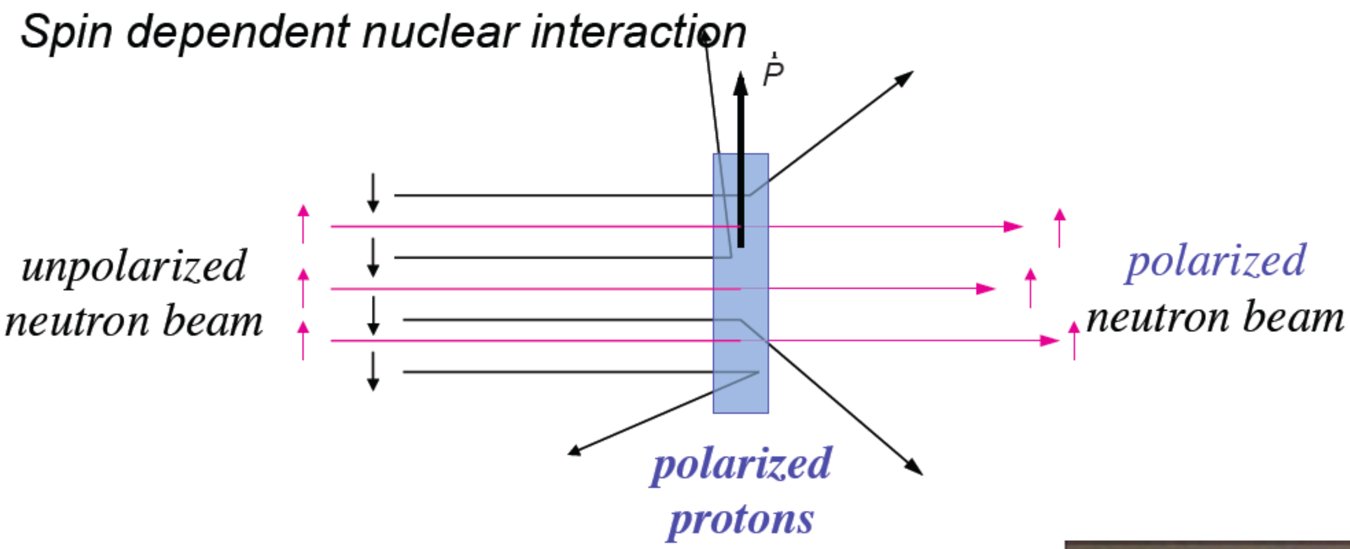
For b = C, only one spin component is diffracted

Materials:
- Fe, Co alloys
- Cu_2MnAl (111) Heusler alloy

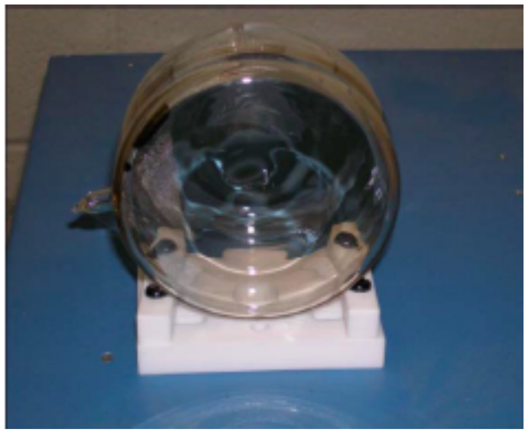
Need for ferromagnetic monodomain
Greatly reduced reflectivity



How to polarize neutrons, part 2

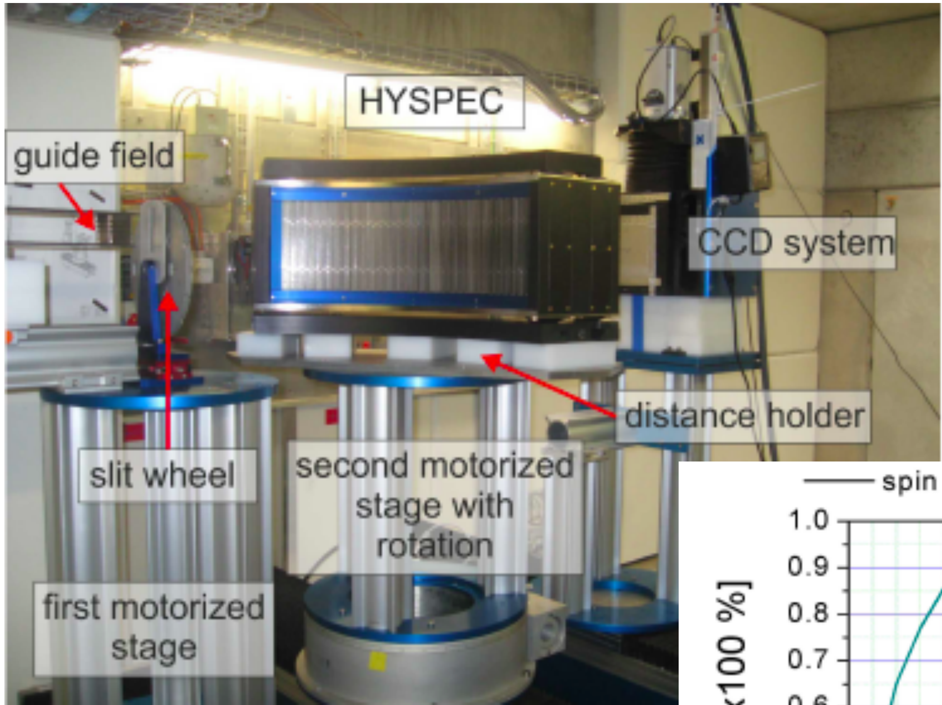


- Polarized nuclei such as protons or ^3He
- P ~ 95% achieved



^3He cell

How to polarize neutrons, part 3



Polarization achieved through spin-dependent total reflection