SPIN and SPIN–OFF

from Particle Physics to Medical Applications

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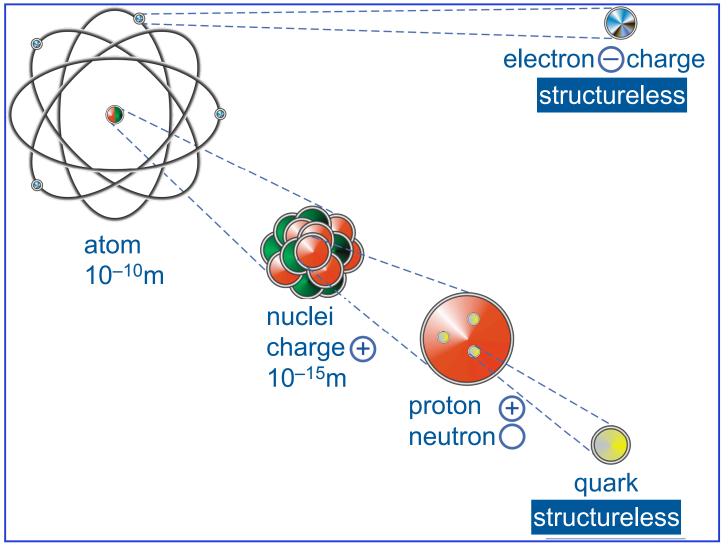
Yamagata, Febr. 29, 2008

What is a Element(ary Particle) ?

~ 450BC. Demokrit : atom (not divisible)

~ 350BC. Aristoteles : earth, water, air, fire

since 1869 Mendelejew : chemical periodic system of the elements with ~ 100 atoms (H; O; He;...)



neutrino ν : structureless

4 particles needed, to build up ordinary matter:

electron; up-quark; down-quark; neutrino

Characterizing of Particles
(world of infinite smallness)

- mass m ⟹ $m_{electron} = 10^{-30}$ kg = 0.5 MeV
- charge q ⟹ $q_{electron} = 1.6 \cdot 10^{-19}$ Cb
- spin (angular momentum) s ⟹ $s_{electron} = 1/2\ \hbar$

etc.

Study of the Particle World

(Microcosmos)

- Scattering experiments
  i.e. bombardment of the objects of study (bacteria ➡ nuclei ➡ protons) with beams (light ➡ electrons etc.)

- detection of scattered particles and newly formed particles with special designed detectors (e.g. COMPASS-spectrometer at CERN)

de Broglie Equation (1924)

particles have wave character

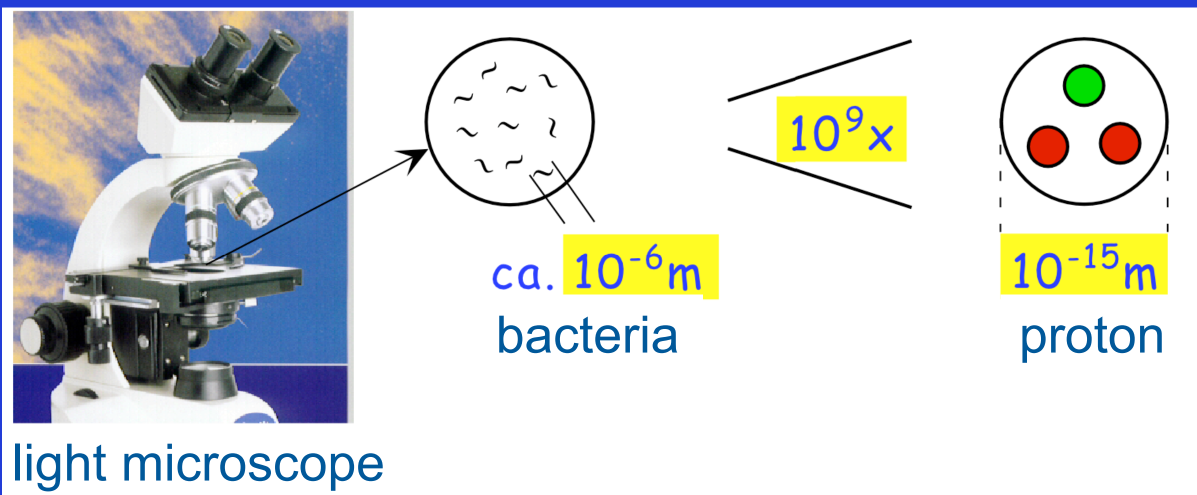
$$E \approx \frac{h}{\lambda}$$

$$E = h \cdot \nu$$

i.e. particles with small wavelength λ have high energy
(visible light ➡ x-rays ➡ γ-rays)

$$E \approx \frac{h}{\lambda}$$

Generally:
the higher the beam energy or the smaller the wavelength, the **more structural details** can be resolved



$\lambda_{\text{visible light}} = 5 \cdot 10^{-7}$m $\qquad\qquad$ $\lambda = 10^{-16}$m

$E = 2$ eV $\qquad \Rightarrow \qquad E > 10^{9}$ eV

$\Rightarrow$ high energy accelerators

SPIN

- fundamental property of all elementary particles
- origin: unknown
- ordering principle (4. quantum number characterizing the atom build-up; spin 1/2-fermions; spin 1-bosons)
- origin for microscopic quantities e.g. magnetization
  ⇒ **M**agnetic **R**esonance **I**maging (**MRI**)
  (nuclei spin resonance)

Spin as 'Intrinsic Property'

Historical: SPIN was a major complication at the description of the fundamental laws

1609 : Kepler-laws …. Conservation of angular momentum

1920's: Classical laws unable, to describe atomic systems

1925 : PAULI PRINCIPLE …. Spin/Statistics laws

1925 : Hypothesis of ´intrinsic´ SPIN …. Uhlenbeck+Goudsmith

1926 : Thomas precession …. correct relativistic calculation

1928 : DIRAC equation …. elegant description of
$(i\hbar\nabla - mc)\,\psi = 0$ a free Spin 1/2-particle
with the electromagnetic field ⇒
Basis for QED – calculable THEORY
Unsurpassed success of Theory + Experiment: $(g\text{-}2)_{e,\mu}$

Today: Standard Model

1970's: 3 families of Quarks + Leptons

1980's: + 5 Vectorbosons

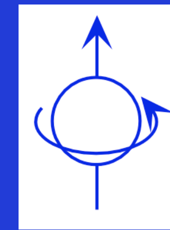
$$\underbrace{\begin{bmatrix} u \\ d \\ e \\ \nu_e \end{bmatrix} \begin{bmatrix} c \\ s \\ \mu \\ \nu_\mu \end{bmatrix} \begin{bmatrix} t \\ b \\ \tau \\ \nu_\tau \end{bmatrix}}$$

SPIN 1/2 - FERMIONS

$$\underbrace{\left[\gamma\,;g\,;W^{\pm}\,;Z^{0}\right]}$$

SPIN 1 - BOSONS

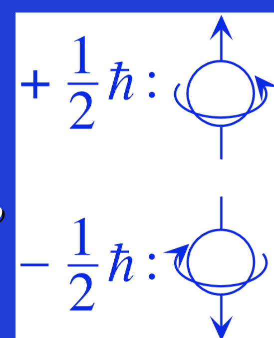
Concept: Spin ≙ Angular Momentum

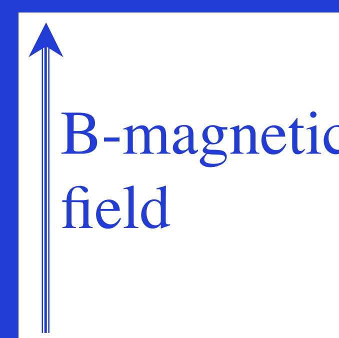


Picture: Particle with SPIN, that rotates around its center of gravity
Precise description: Only in the framework of quantum mechanics

W. Pauli was against the picture of a rotating electron
”It took quite a while, until N. Bohr was successfully, to convince his very critical pupil (W. Pauli) from the ingenuity of this new concept.”
(Phys.-Blätter, April 2000)

e. g. for electron, proton, neutron
(Spin 1/2 - particles) 2 discrete numbers
in a magnetic field (orientation quantization,
energy quantization)

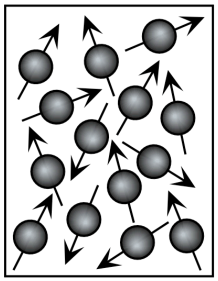




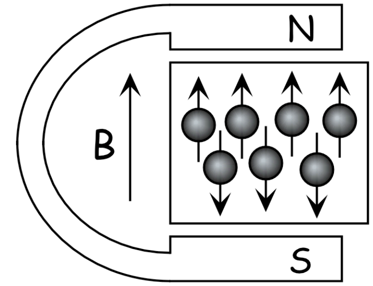
⇨ Particles with Spin can be manipulated with magnetic fields
(analogy: magnetic needle (compass) in the earth magnetic field)

Polarization

= Orientation of Spins in a magnetic field



Without magnetic field:
Randomly orientated spins

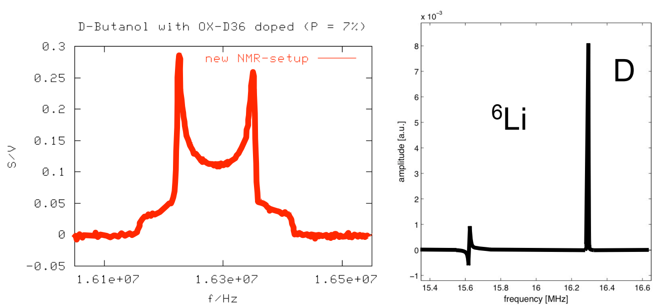


With magnetic field:
Orientation of spin

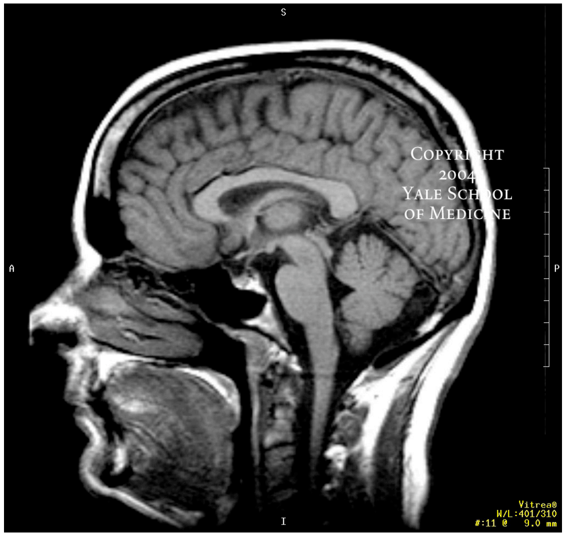
All Spins in magnetic field direction : 100 % Polarization

Change of polarization (e.g. destruction by HF-field) = energy change in the spin system measured by the Nuclei Magnetic Resonance (NMR) method

⇒ resonance signal



⇒ ´visibility` of the particles with spin (mainly protons) by Magnetic Resonance Imaging (MRI)



Dream: 100% polarization of a Spin ensemble

In reality not so easy to realize

Interplay between

polarizing force	≙	magnetic field B
and		
depolarizing force	≙	thermal motion of Spin particles (temperature T – relaxation)

Examples:

$B = 10^{-5}$ Tesla T = 25° Celsius	(earth magnetic field) (room temperature)	P = 10^{-12}%
B = 5 Tesla T = -273° Celsius	(superconducting magnets) (refrigerators)	P = 100%NMR (particle physics)
B = 1 Tesla T = 37° Celsius	(superconducting magnets) (body temperature)	P = 10^{-8}% MRI (medicine)

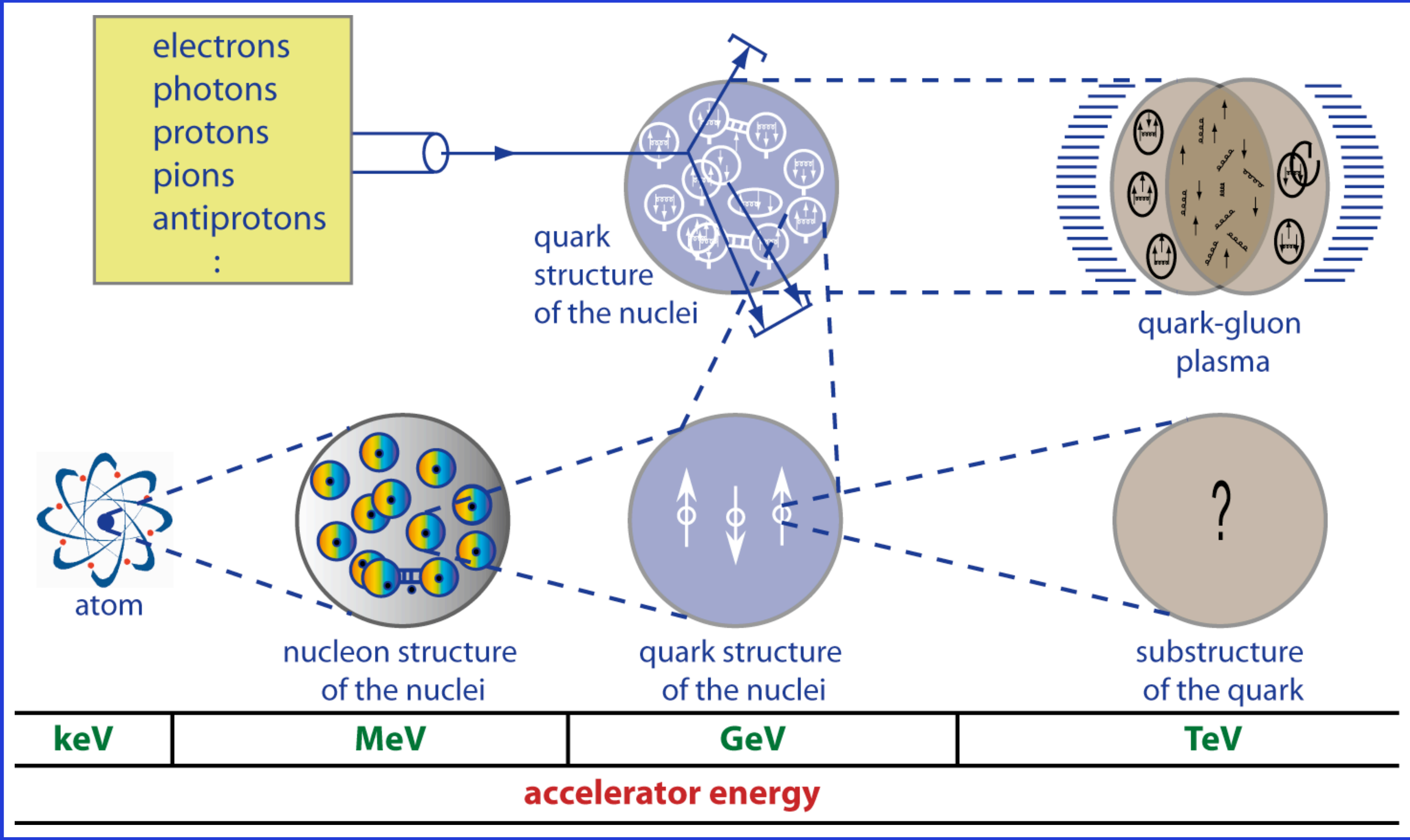
SPIN – OFF

Elementary Nuclei spin (Elementary particle physics)	⇒	Lung diagnostics (Medicine)
Polarized Target	← Apparatus →	Magnetic Resonance Tomograph (MRT)
Subject of study protons, neutrons e.g. $C_4H_{10}O$ (~ 5 x H_2O), ^3He	← Spins →	Objects of information protons (standard), ^3He e.g. H_2O in body tissue
Spin structure of protons and neutrons	← Goal →	Picture from parts of the human body
Polarization degree by Nuclear Magnetic Resonance (NMR)	← Detection signal →	Local information by Magnetic Resonance Imaging (MRI)
Proton, ^3He-density Relaxations	← Parameter →	Proton, ^3He-density Relaxations

Particle Physics

Goal: Experiment

Nucleons and nuclei bombarded with



Particle Physics

Goal: Theory

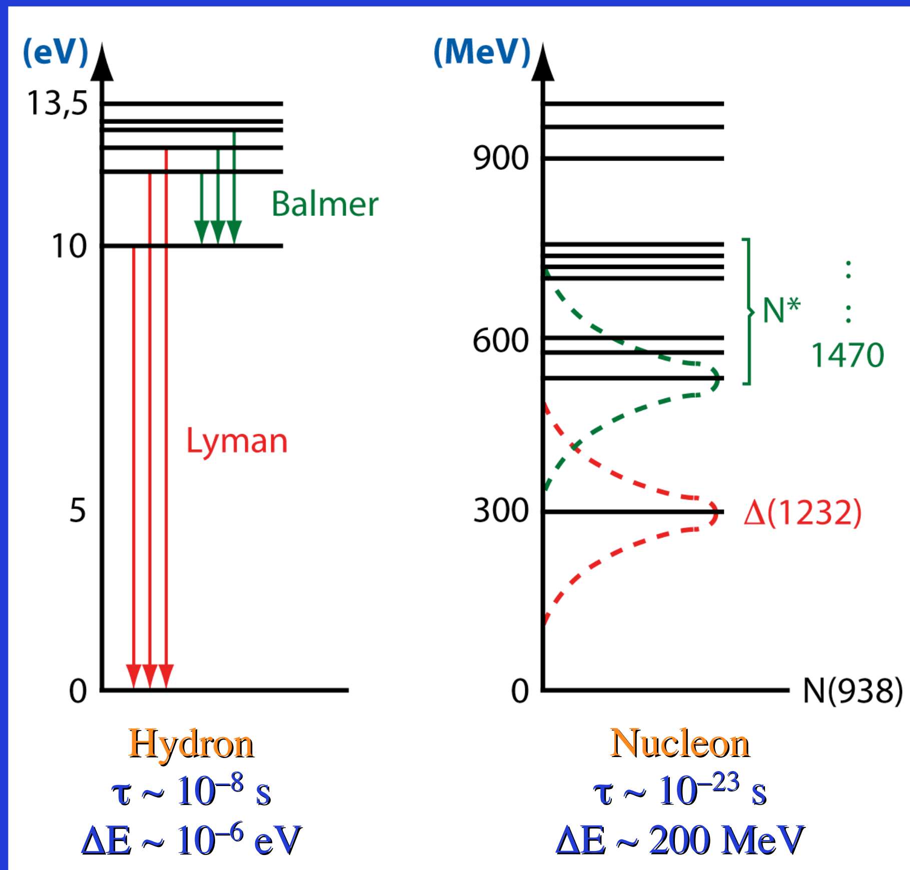
Understanding of the material structure by means of

QCD, which has problems at the description of the Quark-Gluon-Dynamics in the confinement region (several GeV; α_s strong)

many models

systematic experimental research

Possible solution: Study of excited resonant states of the nucleon



Reaction for the study of excited nucleon state

e.g. Bonn (2.5 GeV electron synchrotron)

INS (1.4 GeV electron synchrotron) ➡ Nagoya activities

$\gamma N \rightarrow \pi N$ Pion Photo production

Experimental progress in the **GeV-region** by new facilities:
COSY ; ELSA ; MAMI ; SPRING8 ; TJNAF ...
with a **big SPIN program**
and at higher energies upgraded facilities for **SPIN Studies**

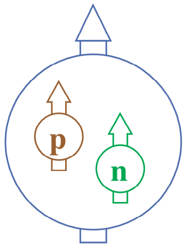
SLAC	—	1990 - 1996
CERN	—	SMC finished; COMPASS runs
DESY	—	HERMES finished
BNL	—	RHIC started

Structure Studies :
- meson production
- resonance excitation
- threshold behaviour
- form factors
- structure functions
- spin dependence
- sum rules

1. Step : Measurements of Cross-Sections
but : Averages of many pure SPIN Cross-Sections

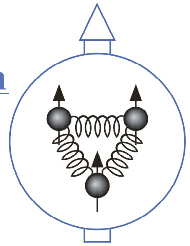
Experiments: 'Composed' Spin

Nuclei



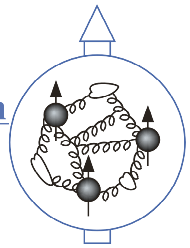
– Interaction is spin dependent
e.g. Proton-Neutron coupling
to I = 1 (Deuteron)
no Di-Proton ; Di-Neutron

Nucleon
effective models; χPT



e.g. Baryonresonanz Δ

Nucleon
pQCD



$$I_Z^N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Z$$

⟹ Key experiments at CERN, SLAC, DESY
Deep inelastic polarized Lepton-Nucleon scattering

Studies of SPIN effects ⇒

POLARIZATION-EXPERIMENTS

Renaissance: improved polarization techniques for beams & targets

2 Sum rules as motors for the development of Pol. Targets & Pol. Beams

– **Bjorken Sum Rule (1966)**

$$\int_0^1 \left[g_1^p(x) - g_1^n(x) \right] dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \cdots$$

– **Gerasimov-Drell-Hearn (GDH) Sum Rule (1965)**

$$\int_0^\infty \left(\sigma_{3/2} - \sigma_{1/2} \right) \frac{d\nu}{\nu} = 2\pi^2 \alpha \frac{\kappa^2}{m^2}$$

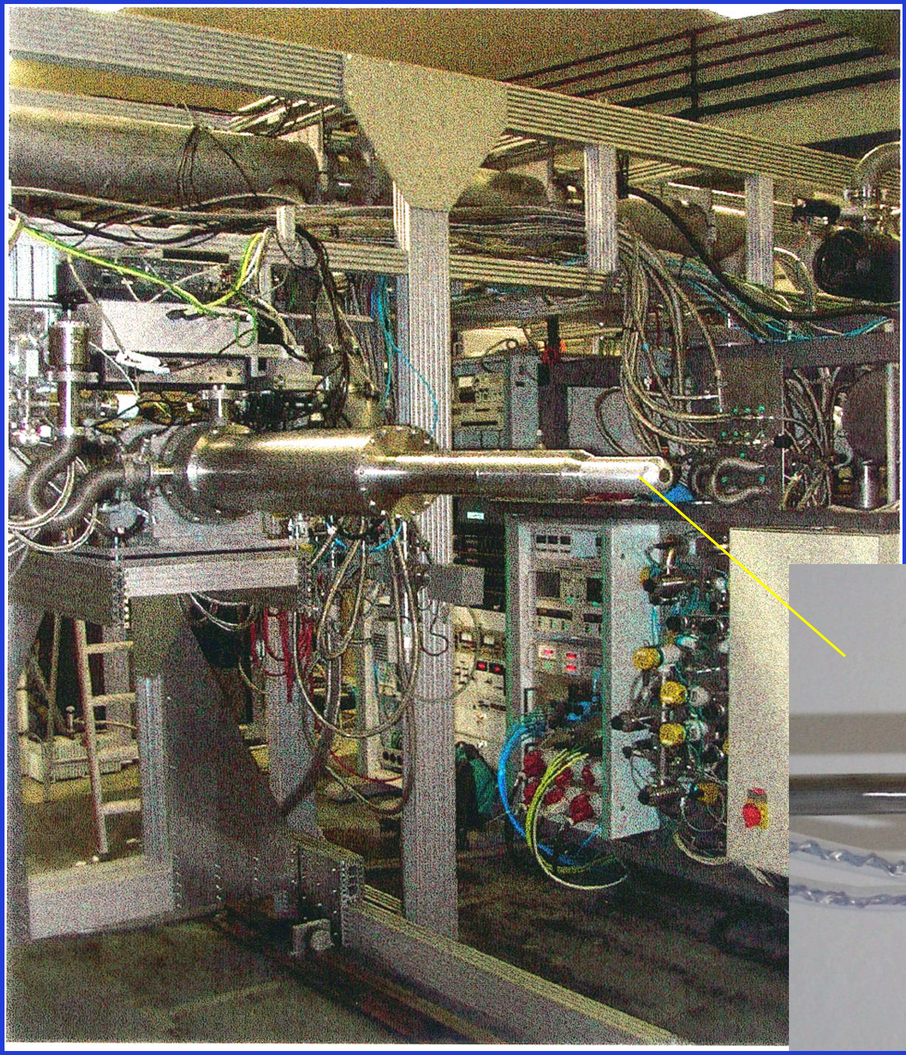
90‘ due to technical difficulties experimentally not tested

Solution :

– Highly polarized electron beams: $P_e \sim 80\%$ (SLAC, Nagoya)
– High density and highly polarized ^{3}He-gas targets: $P_{He} \sim 50\%$ (Mainz, Princeton)
– New solid target materials with high radiation hardness: NH_3, ND_3, ^{6}LiD (Bonn, Bochum)
– Highly polarized H and D gas target cells (Erlangen, Wisconsin)
– Solid target & 4π-detection (Bonn, Mainz, Nagoya)
– Highly polarized solid deuteron targets (Bochum)

Frozen Spin Target (GDH - Mainz, Bonn)

Marriage of polarized solid target and 4π-particle detection (Bonn)

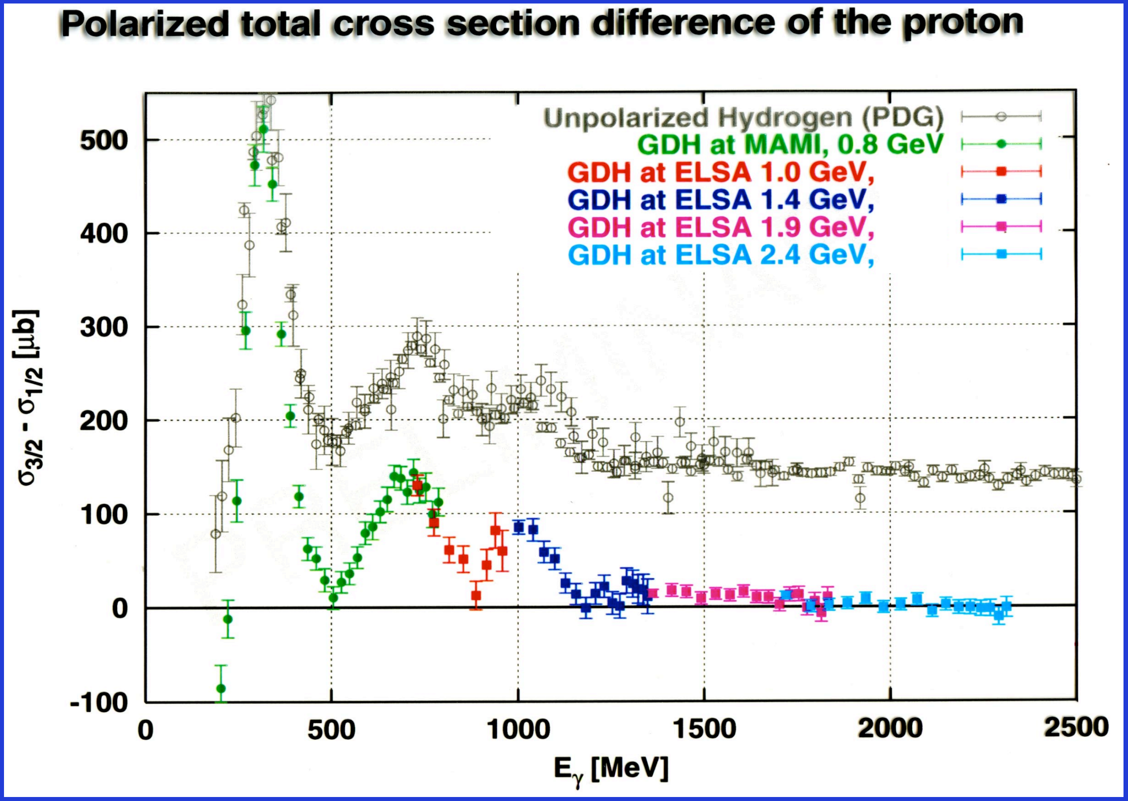


0.64T magnetic ‚holding‘ coil

Results: GDH Sum Rule

– GDH sum rule at the proton ✓

– Additional results for double polarization observable in single and multiple pion photoproduction → later

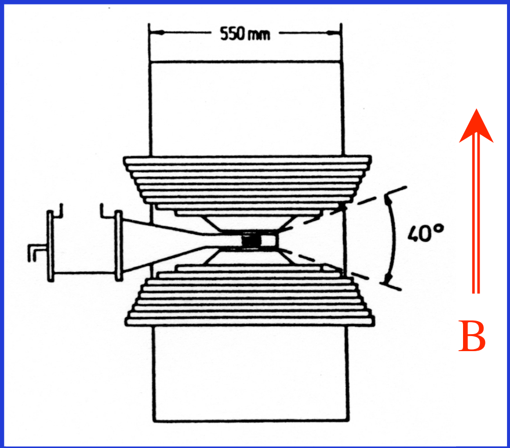


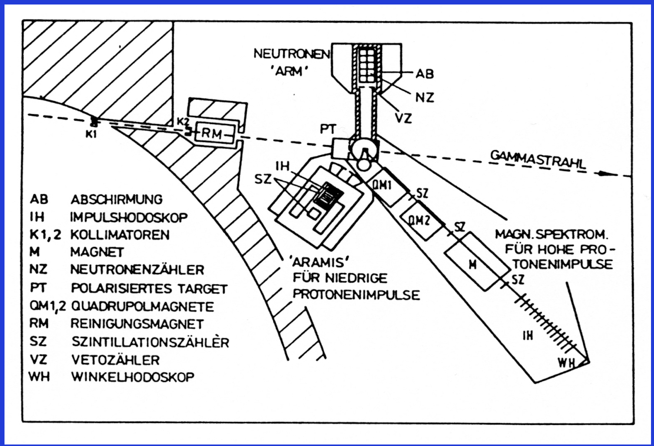
– GDH sum rule at the neutron < 0.8 GeV (Mainz)

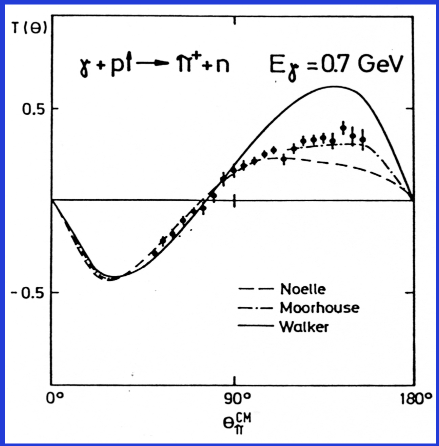
0.8-1.8 GeV (Bonn)

Target Asymmetry Measurements: y-Polarization

1975 (Bonn) – spectrometer acceptance < 5msr

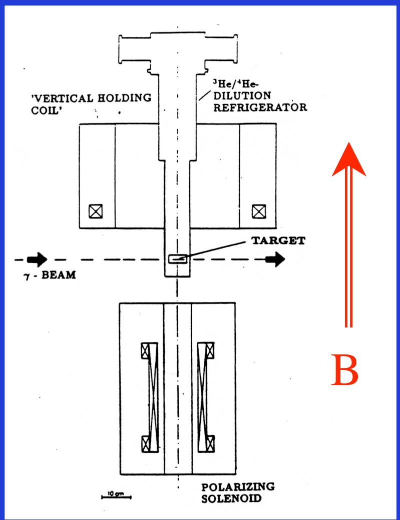


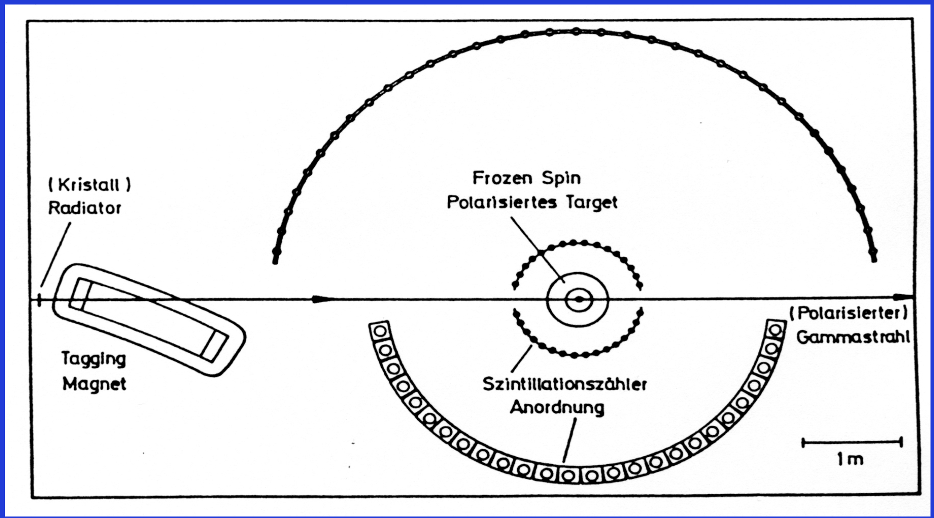




Phys. Lett. 63B(1976)107

1992 (Bonn) – detector acceptance ≈ 1sr





$\gamma p\uparrow \rightarrow \pi^+ n$

216 data points

$270\text{MeV} < E_\gamma < 800\text{MeV}$

$\gamma p\uparrow \rightarrow \pi^0 p$

52 data points

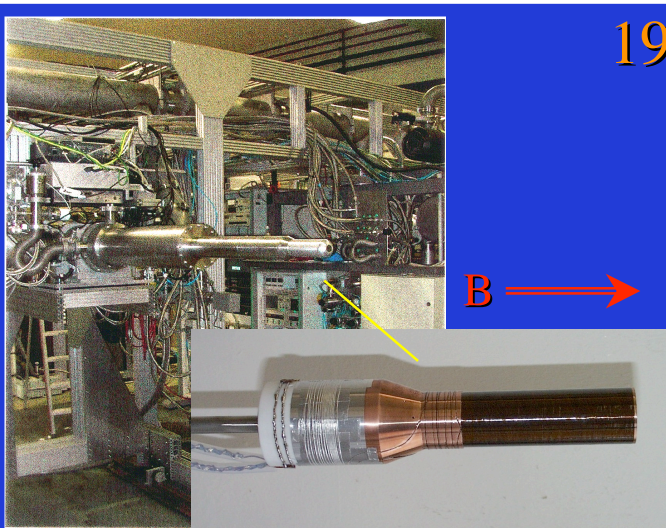
$272\text{MeV} < E_\gamma < 573\text{MeV}$

$\theta_{CMS} = 35°–135°$

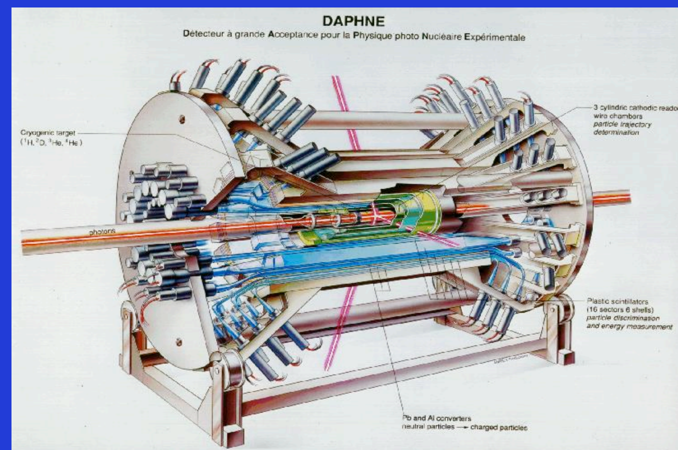
Nucl. Phys. A601, 319, 1996

Double Polarization Measurements: z-Polarization

1998 – 4π-detection



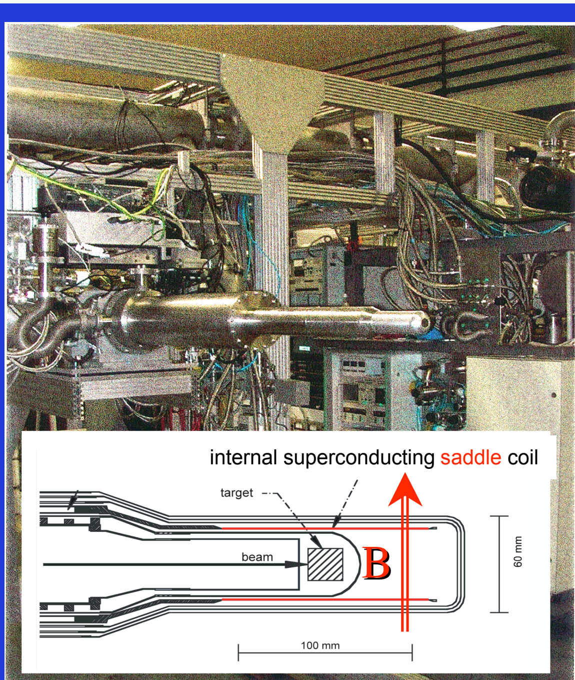
B →

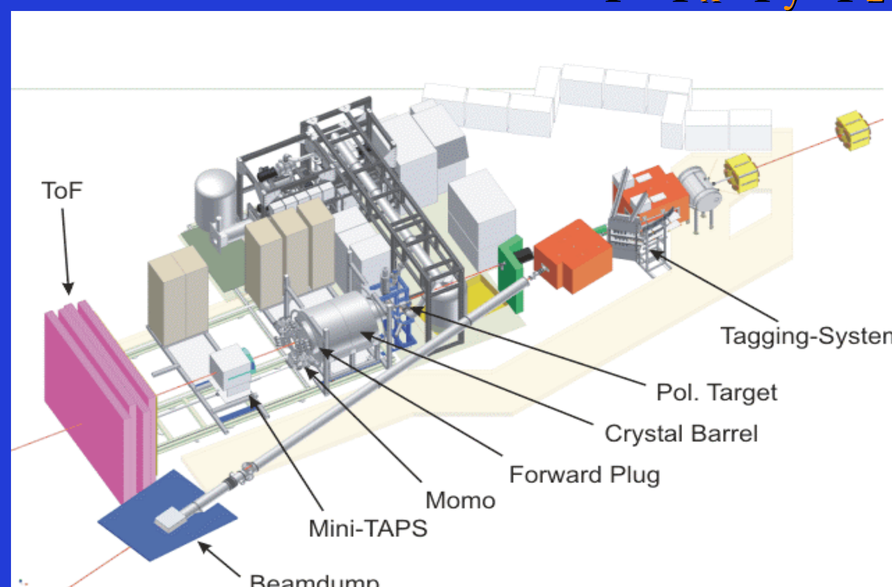


GDH-measurements in Mainz and Bonn

Phys. Rev. Lett. 87, 022003, 2001
Phys. Rev. Lett. 91, 192001, 2003

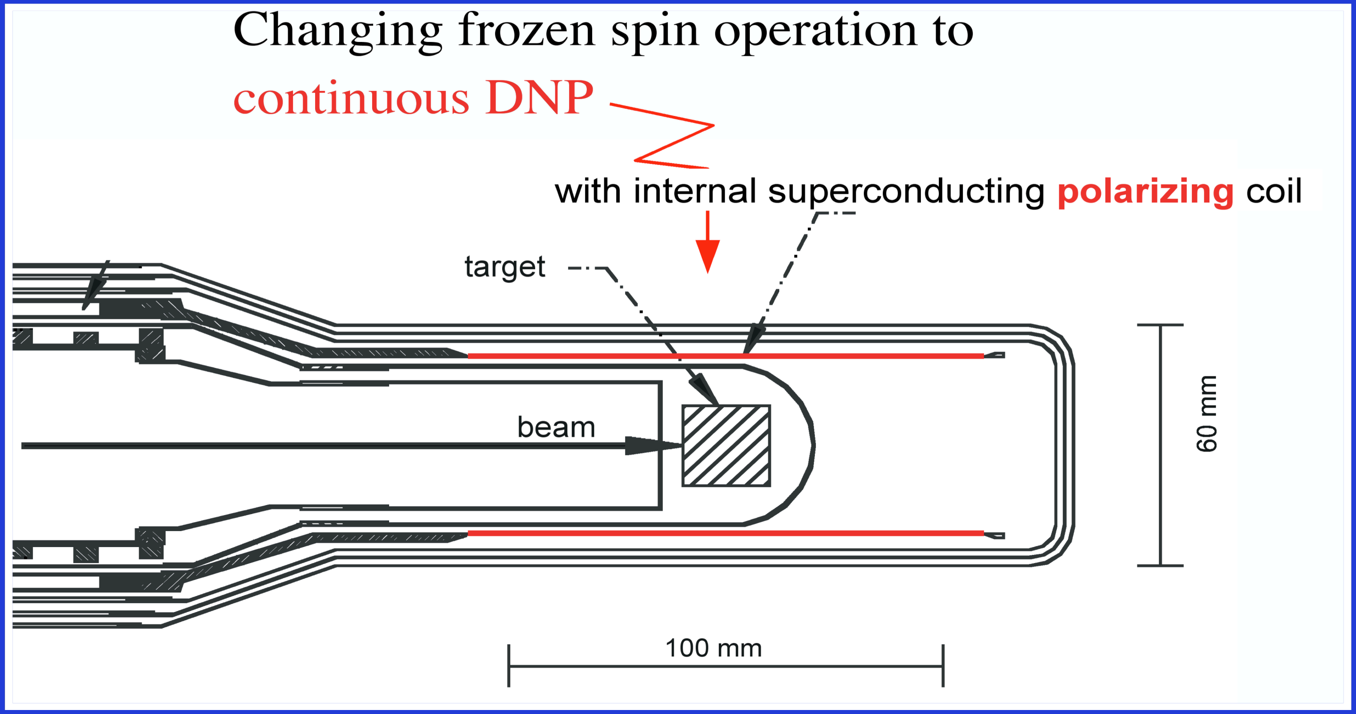
> 2007 – 4π-detection + $\vec{p}\,(p_x, p_y, p_z)$





Complete exp.
$\gamma N \rightarrow \pi N$

Finally, there is a Goal



Advantages: – high beam intensities tolerable < 5nA at high polarization
– more smooth data taking periods (no interruption by mechanical manipulations)

Difficulties: – magnet field homogeneity $< 10^{-3}$ for proton targets (1. step)
– high current input in $^3He/^4He$ refrigerator > 100A for > 1.5T

Results (CERN, SLAC, DESY)

– from deep ineleastic polarized lepton-nucleon scattering

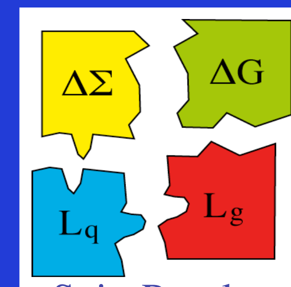
(a) Bjorken sum rule ✓

(b) 

$$S_{nucleon} = \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$

contributions from: Quark spin ($\Delta\Sigma$), Gluon spin (ΔG), angular momentum Quark (L_q), angular momentum Gluons (L_g)

Quark spin → ≈ 0.3



Spin-Puzzle

– photon-gluon fusion: COMPASS at CERN

→ $\Delta G/G$ = small (preliminary)

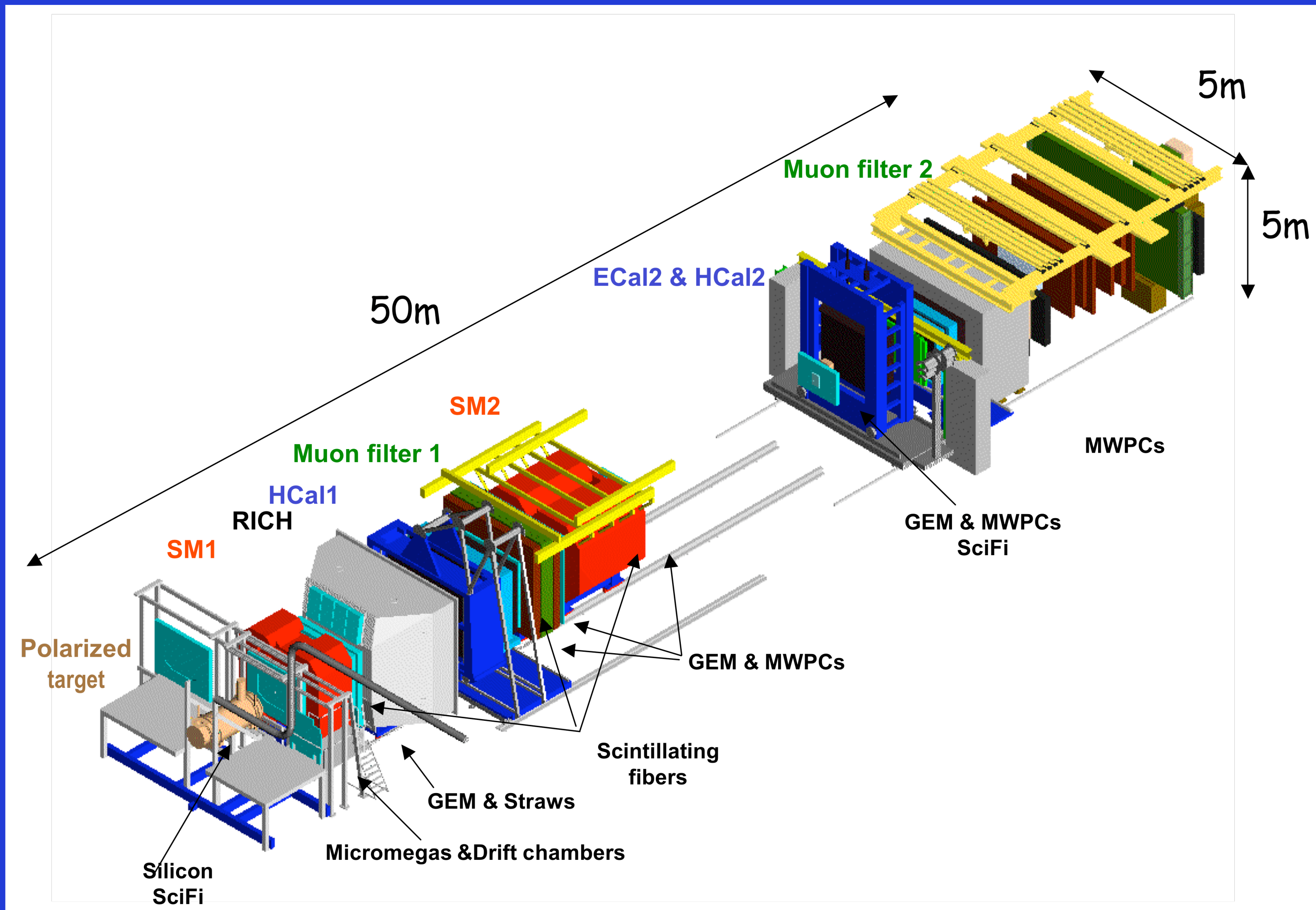
– L_q → experiments planned

– transversity measurements → experiments done

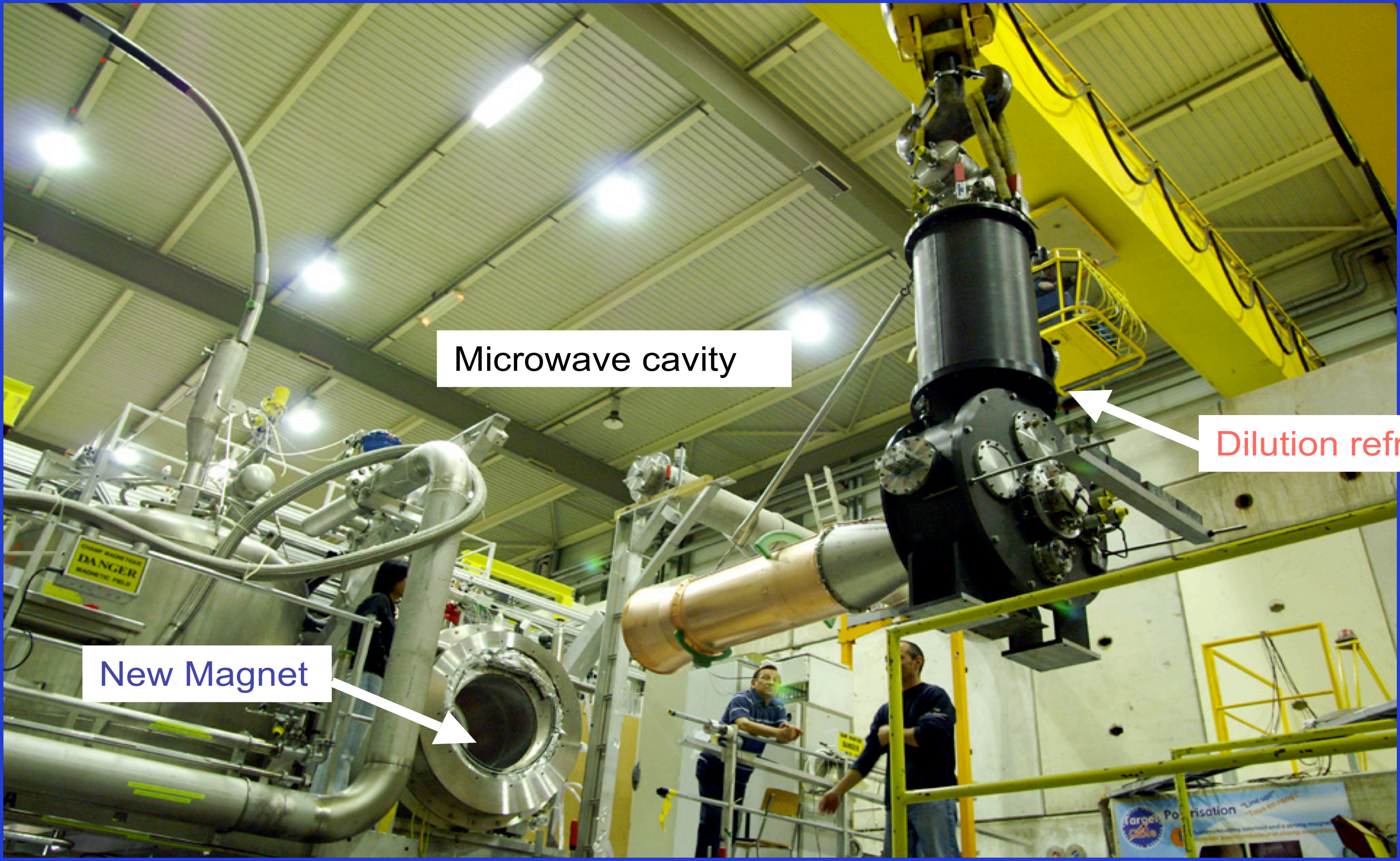
COMPASS Experiment at CERN

Beam: $2.8 \cdot 10^8$ μ^+/spill (4.8s/16.2s)
160 GeV/c
Target: ^{6}LiD

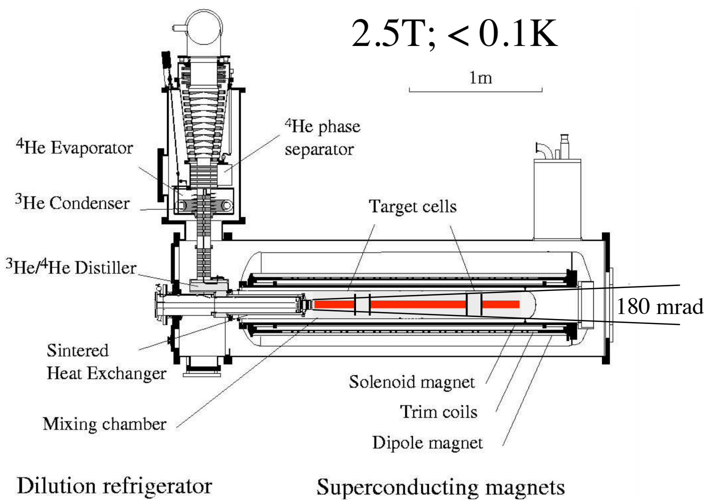
Luminosity: $\sim 5 \cdot 10^{32}$ cm^{-2} s^{-1}
Polarization:
- Beam: –76%
- Target: 51%



COMPASS Target Equipment at CERN



COMPASS Target at CERN



(Bochum, Saclay, Yamagata)

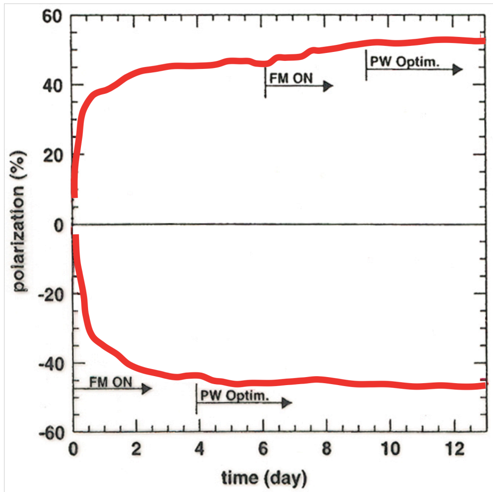
4 possible target spin combinations

$\rightarrow \leftarrow \rightarrow$
$\leftarrow \rightarrow \leftarrow$ } DNP – mode $B_{pol. (solenoid)} = \rightarrow$

$\uparrow \downarrow \uparrow$
$\downarrow \uparrow \downarrow$ } Frozen spin mode $B_{holding (dipole)} = \uparrow$

} polarization reversal by magnetic field reversal

		NH_3	Butanol	d-Butanol	^{6}LiD
Polarization of the nuclei	P_N	H: 0.90	H: 0.90	~~0.50~~ 0.8	D, ^{6}Li: 0.50
Polarization of the nucleons	P_n	0.90	0.90	0.463 0.74	0.463 in D 0.433 in ^{6}Li
(fractional) Dilution factor	f	0.176	0.135	0.238	D, ^{6}Li: 0.25
Effective polarization	P_{eff}	0.158	0.122	0.110	0.224
Density (g/cm^3)	ρ	0.85	0.99	1.10	0.84
Packing factor	κ	0.60	0.60	0.60	0.55
Figure of merit (10^{-3}g/cm^3)	F	12.7	8.8	~~8.0~~ 20.5	23.2



$\overline{P}_{^6LiD} = 51\%$

(2001; 2002; 2003; 2004; 2006)

Deep inelastic scattering on polarized Deuterons

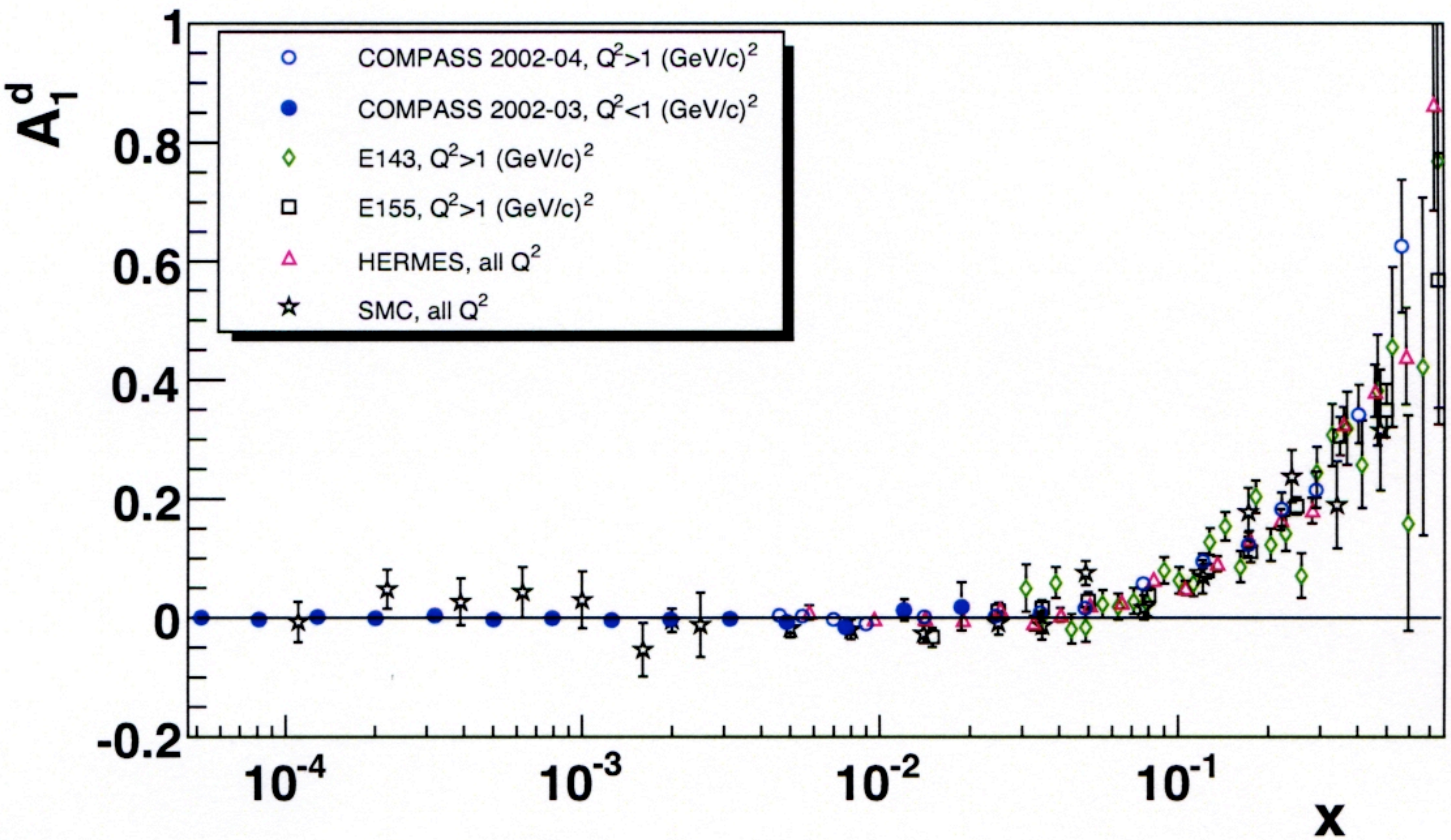
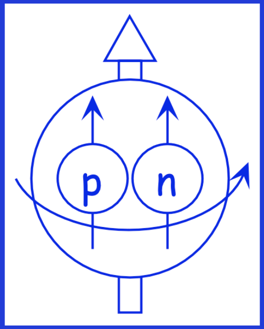


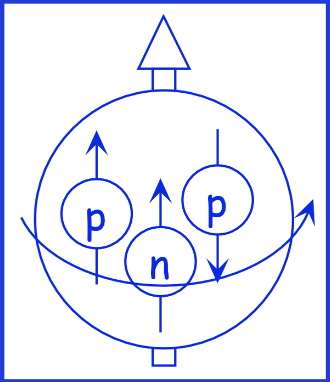
Figure 8: The asymmetry $A_1^d(x)$ as a function of x at the measured values of Q^2: the results for $Q^2 < 1$ (GeV/c)^2 obtained in this analysis are compared with previous results at different values of Q^2 from COMPASS [12], SMC [8, 13], HERMES [11], SLAC E143 [9] and SLAC E155 [10]. The E155 data correponding to the same x have been averaged over Q^2. Errors are statistical.

Polarized Neutrontarget

➢ Deuteron as Spin 1-particle



➢ ^{3}He as Spin 1/2-particle



^{3}He-gas highly polarizable (P ~ 50%)

by means of dynamic methods (laser)

at room temperature (300 K)

and small magnetic field (1 mT)

in glass cells

} polarized ^{3}He easily transportable

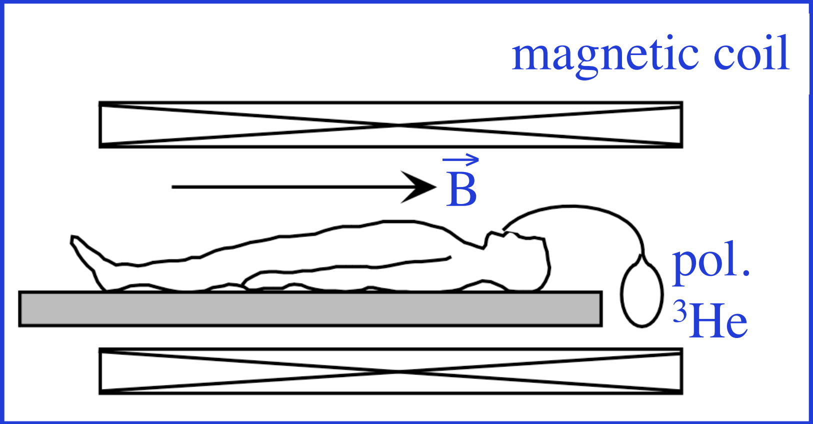
→ Deep inelastic scattering experiments e.g. at SLAC

Modern Lungdiagnostics

Air (77% nitrogen
21% oxygen
2% +argon, ^{4}He ...) } no MRI-signal

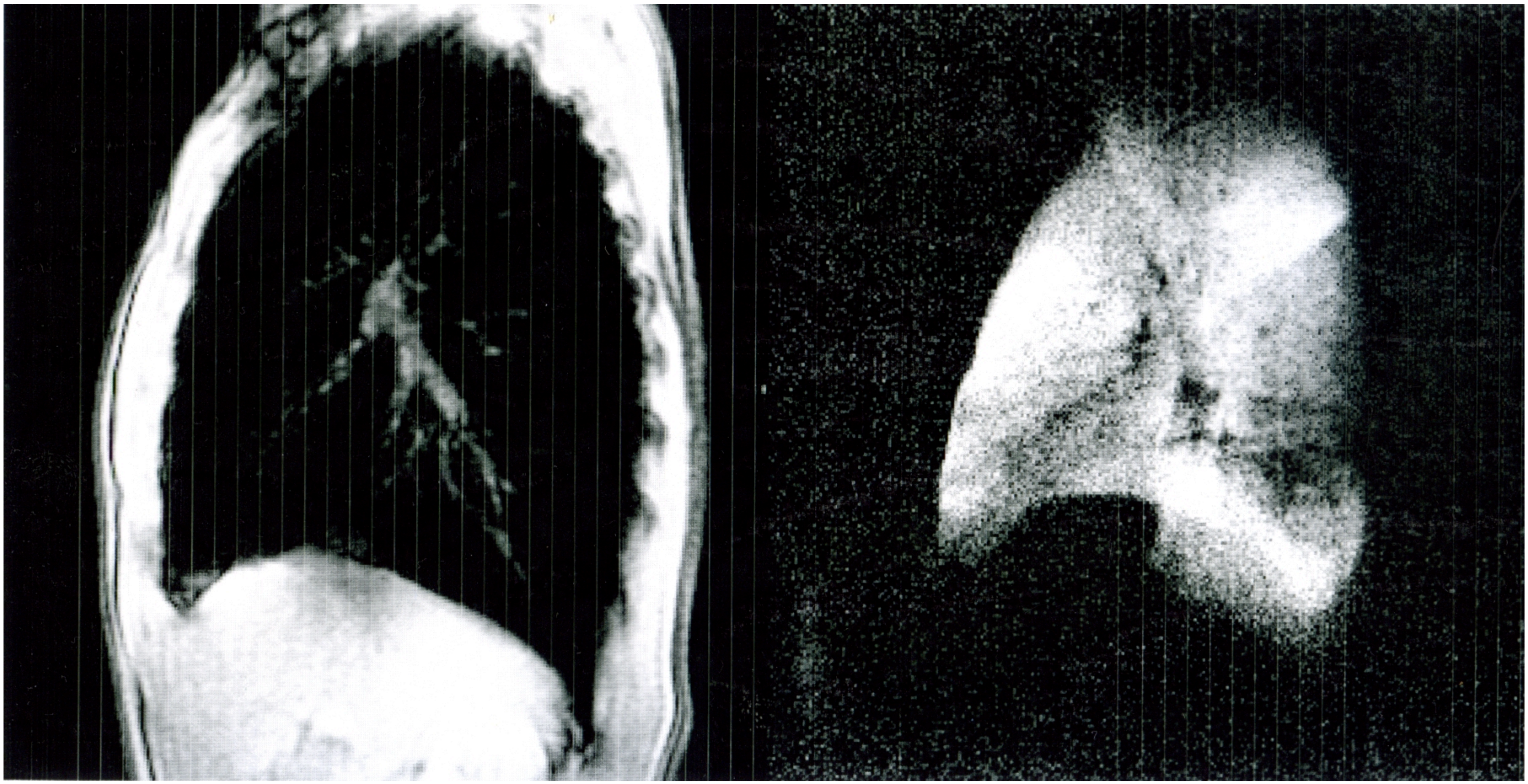
Question: Information about lung and its ´airchannels´
pulmonary alveoli (about 400 million
diameter: 0.2 mm
area: ~10 m^2)

Inhale polarized ^{3}He-gas as patient in a MRI-tomograph
➥ ^{3}He-MRI ⇒ picture of lung



MRI-Picture of Lung

Hydrogen (^{1}H) ^{3}Helium



Heidelberg, Nov. 1995

Polarized Target Materials by DNP

Commonly used in particle physics experiments

Polarizable					Radiation
Materials and chemical composition	Dopant and method[a]	Nucleons % by weight	B/T Tesla/K	Polarization %	Characteristic flow 10^{14} particles/cm^2
Butanol C_4H_9OH	EHBA Cr (V) Ch	13.5	2.5/0.3	±93	3 – 4
Ammonia $^{14}NH_3$, $^{15}NH_3$	$\dot{N}H_2$ Ir	17.5, 16.6	5/1.0	+97 −100	70, 175[b]
^6LiD	F-center Ir	50	2.5/0.2	±57	400
D-Butanol	Finland D36	23.8	2.5/0.2	±79	not measured

[a] Ch: chemically doped, IR: doped by irradiation
[b] In NH_3 there are two distinct regions of decay

DNP for

Particle physics

Proton (Deuteron) rich material
(see before)

polarized

at $T < 0.2$ K ($^3He/^4He$)
and $B = 2.5$ T (70 GHz)

⇓

High polarization (80–100%)
with good polarization resistance
against radiation damage

⇓

Experiments

Medical applications

^{13}C-enriched material
(e.g. urea; pyruvic acid)

polarized

at $T = 1.2–1.3$ K (pure ^4He)
and $B = 3.5$ T (98 GHz)

⇓

Reasonable polarization (40%)

⇓

⇒ Fast dissolution of frozen material

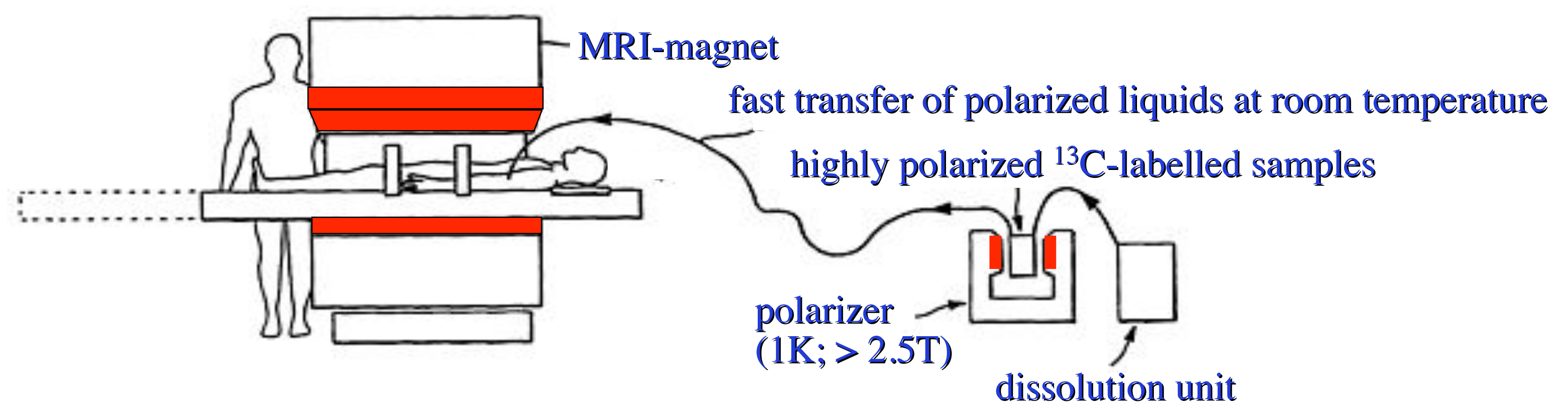
⇓

Hyperpolarization in liquid state
transfered for in vivo studies

Adopted innovative Technology

Spin oriented ^{13}C-nuclei for medical diagnostics

- Optimized production path for hyperpolarized ^{13}C-labelled contrast agents
  Improvement twofold:
  → high degree of polarization gives sufficient time at room temperature for in vivo studies (exponentiell decay of nuclei spin polarization)
  → transportable polarizers for use in medical environment



All together:

Even after 45 years of
Dynamic Nuclear Polarized (DNP)
solid targets
in particle physics
the next future will be bright, too

enhanced by an immense interest
for medical and biochemistry
applications.