RUB

Experimentalphysik I
Arbeitsgruppe Physik der Hadronen und Kerne | Prof. Dr. W. Meyer
G. Reicherz, Chr. Heß, A. Berlin, J. Herick
and in behalf of the A2-Collaboration

New Spin-Physics Experiments with Frozen-Spin Target at MAMI

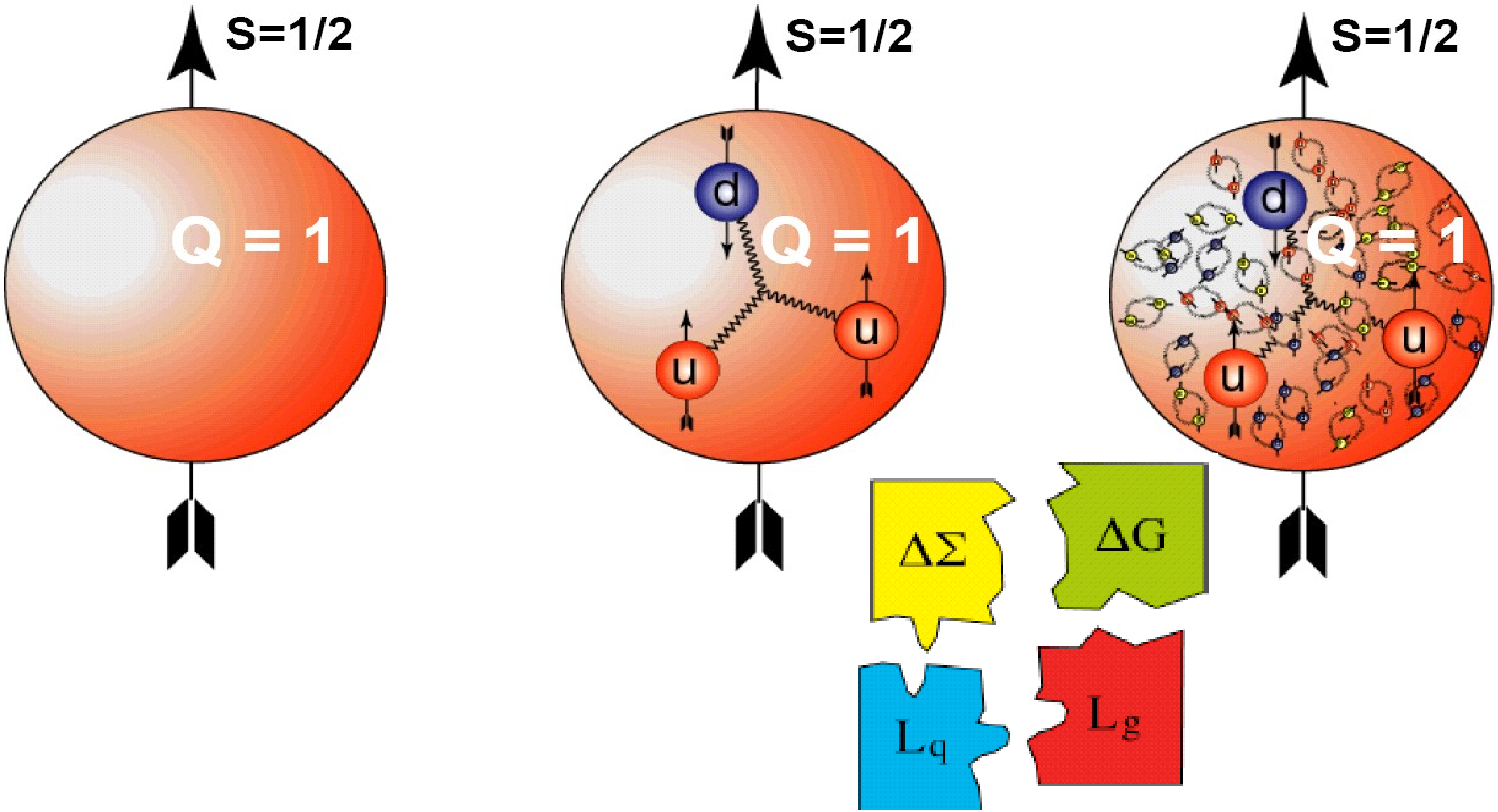
CB-MAMI / A2

20.06.2011 Cairns

- Motivation
- Polarization Experiments
- MAMI and A2 Laboratory
- Polarized Target
- Recent Results
- Summary

Motivation 1

Picture of a Proton (Skale fm).



Spin-Puzzle

Motivation 2

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

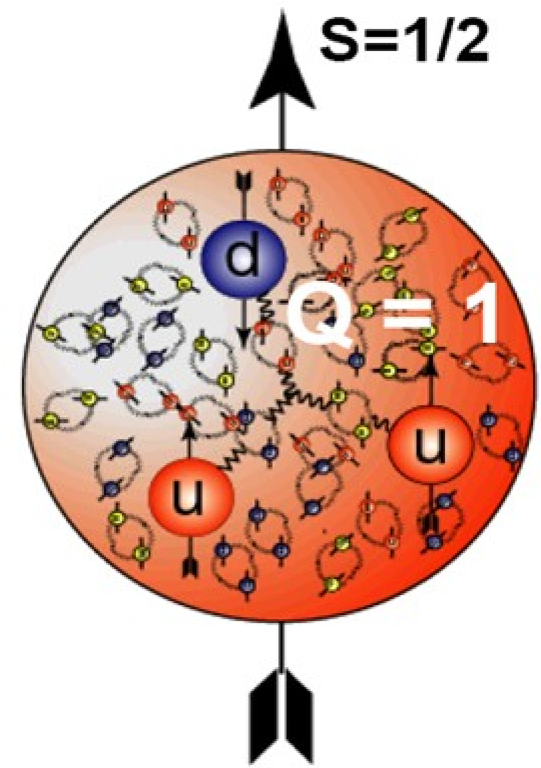
Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

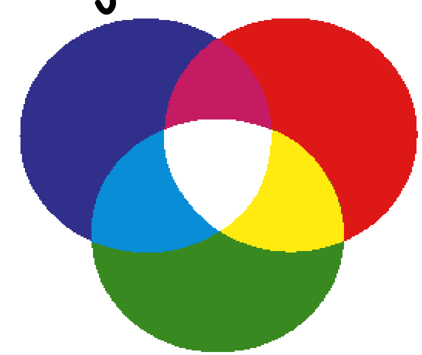
BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0



QCD Colourless objects:
Baryons (qqq)
Mesons ($q\bar{q}$)



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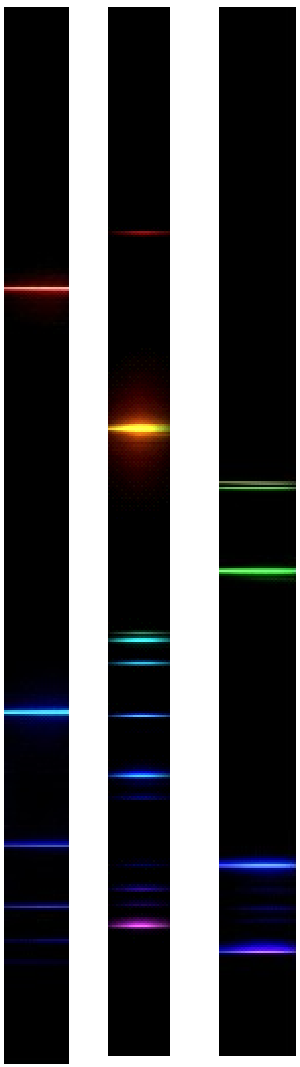
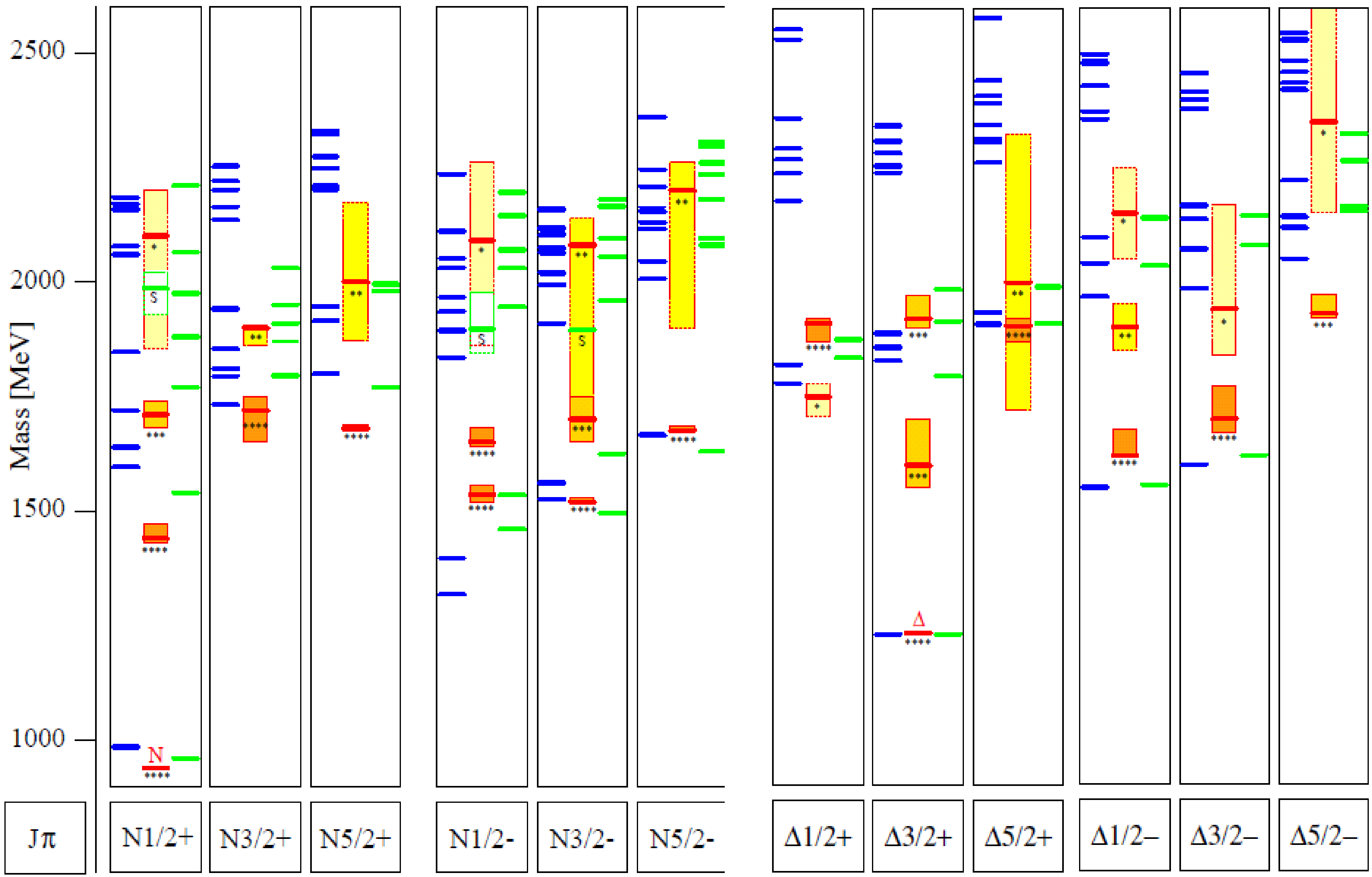
Excitation Spectrum of the Nucleon





H He Hg Nucleon

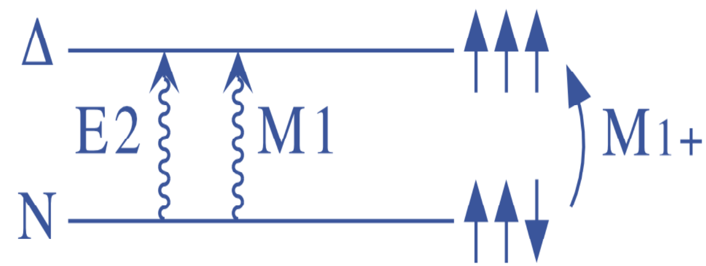
Atom

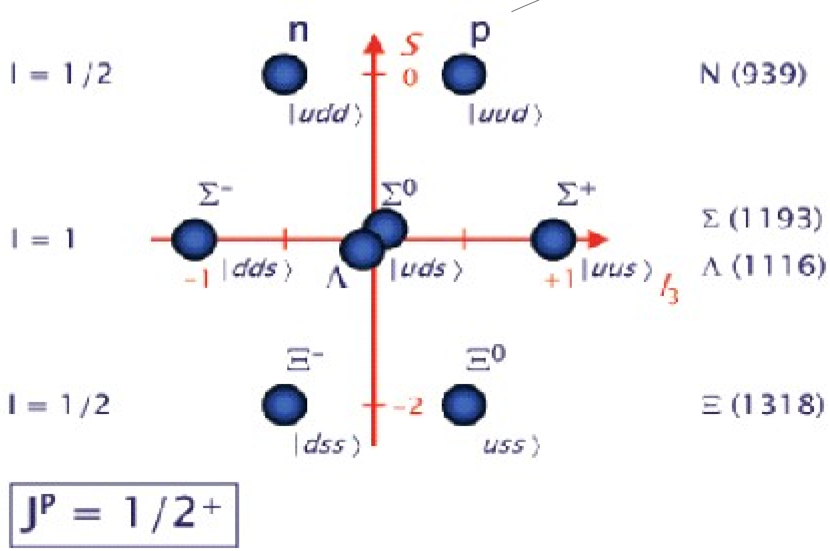
Löhrig, Metsch, Petry, Eur.Phys.J. A10 (2001) 395-446

The light baryon spectrum in a relativistic quark model

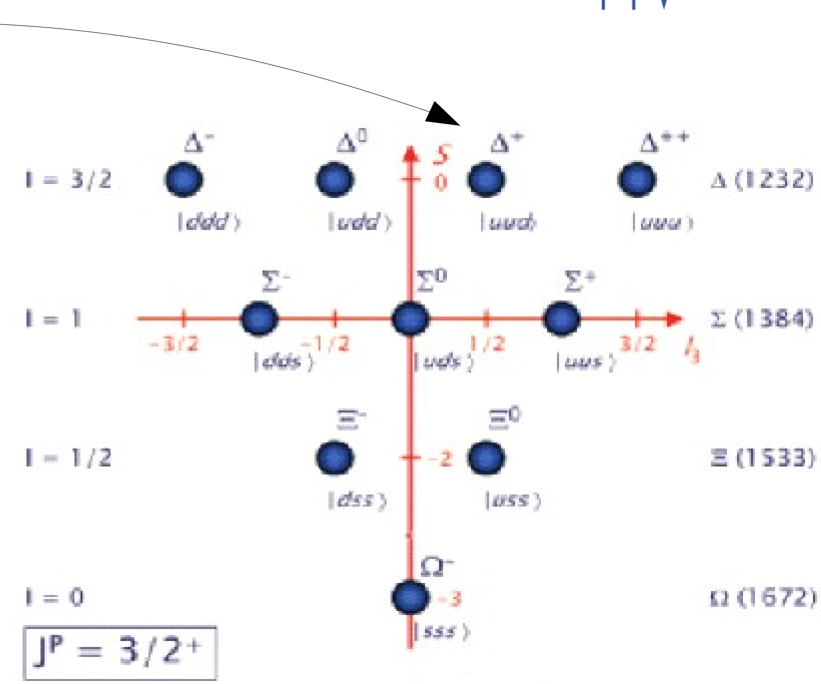
Excitation Spectrum of the Nucleon

Quark Model (Simple Constituent quark picture)
Classification of Baryons qqq; only uds





Oktett



Dekuplett

$|qqq\rangle_A = |color\rangle_A |space;spin;flavour\rangle_S$

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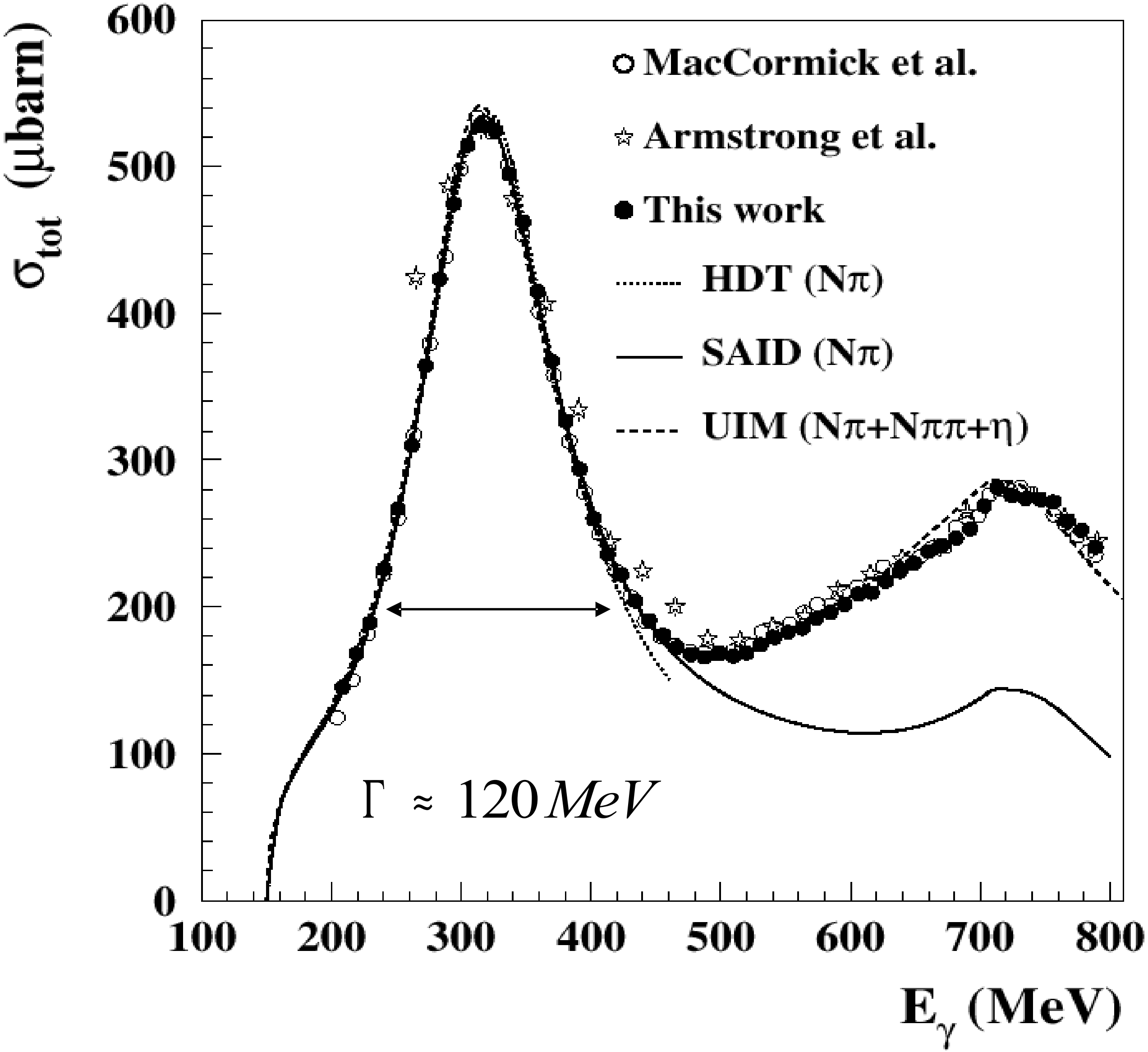
What is the nature of the Nucleon Resonances?

Unpolarized total photoabsorption cross section



- Excitation inner DoF
- Molecule
- Quark – Diquark Structure
- Dynamical Generation
- …….?

Phys. Rev. Lett. 87, 022003 (2001)

Phys. Rev. Lett. 84, 5950 (2000)

… Nucl. Phys. A642, 561 (1998)

— Phys. Rev. C 53, 430 (1996); SP01

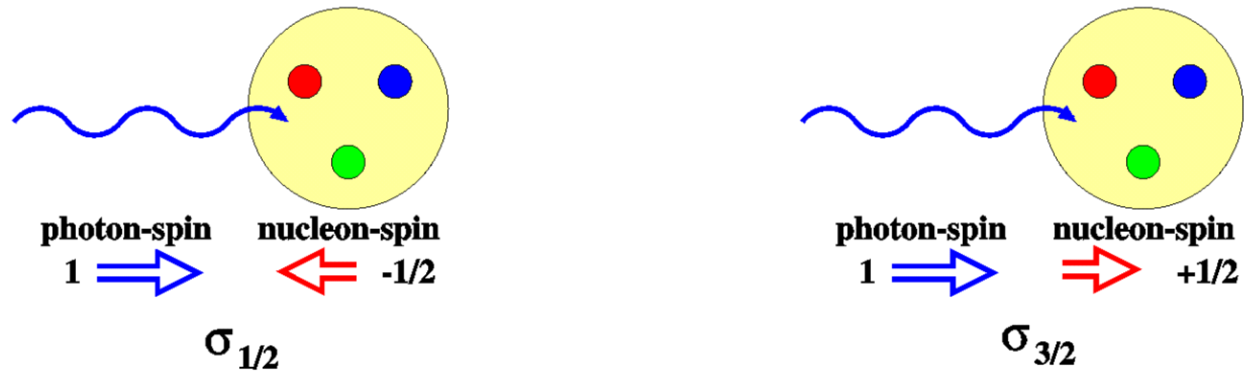
--- Nucl. Phys. A645, 145 (1999)

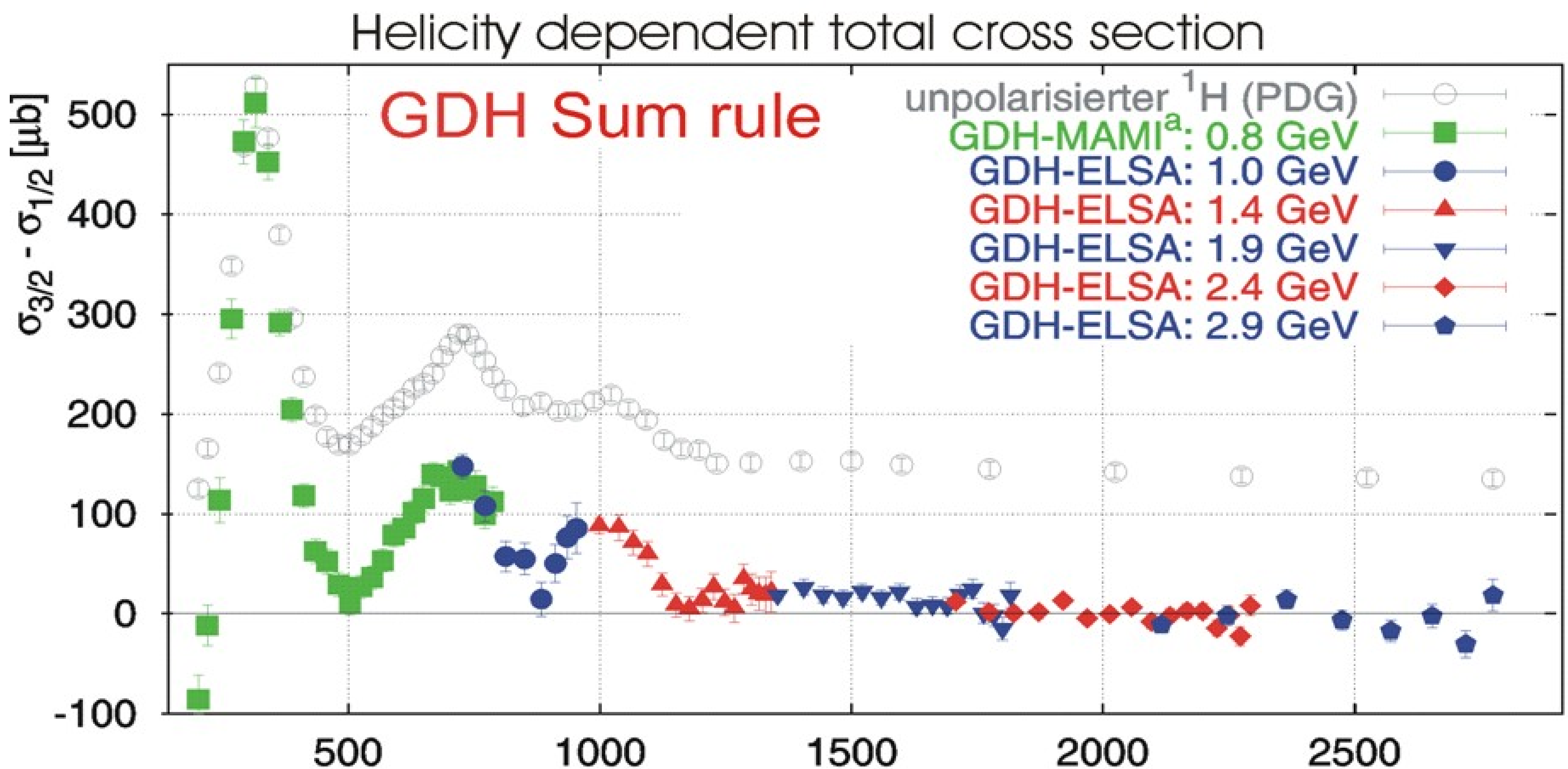
Lifetime $\tau = \frac{\hbar}{\Gamma}$

$\hbar = 6.582 \cdot 10^{-22}\,MeV \cdot s$

$\tau \approx 10^{-24}\,s$

GDH Proton





MAMI data: J. Ahrens et al., Phys. Rev. Lett. 87 (2001) 022003
ELSA data: H. Dutz et al., Phys. Rev. Lett 91 (2003) 192001

Nature and Properties of nucleon resonances

⇒ Polarization observables used to disentangle broad, overlapping resonances.

Observables in pseudoscalar meson prod.

(Barker, Donnachie & Storrow Nucl Phys B95 (1975))

$$
\begin{aligned}
\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{unpol} \{ 1 - & P_\gamma^{lin}\Sigma\cos 2\phi + P_x(P_\gamma^{circ}F + P_\gamma^{lin}H\sin 2\phi) \\
& + P_y(T - P_\gamma^{lin}P\cos 2\phi) + P_z(P_\gamma^{circ}E + P_\gamma^{lin}G\sin 2\phi) \\
+\sigma'_x[& P_\gamma^{circ}C_x + P_\gamma^{lin}O_x\sin 2\phi + P_x(T_x - P_\gamma^{lin}L_z\cos 2\phi) \\
& + P_y(P_\gamma^{lin}C_z\sin 2\phi - P_\gamma^{circ}O_z) + P_z(L_x + P_\gamma^{lin}T_z\cos 2\phi] \\
+\sigma'_y[& P + P_\gamma^{lin}T\cos 2\phi + P_x(P_\gamma^{circ}G - P_\gamma^{lin}E\sin 2\phi) \\
& + P_y(\Sigma - P_\gamma^{lin}\cos 2\phi) + P_z(P_\gamma^{lin}F\sin 2\phi + P_\gamma^{circ}H)] \\
+\sigma'_z[& P_\gamma^{circ}C_z + P_\gamma^{lin}O_z\sin 2\phi + P_x(T_z + P_\gamma^{lin}L_x\cos 2\phi) \\
& + P_y(- P_\gamma^{lin}C_x\sin 2\phi - P_\gamma^{circ}O_z) + P_z(L_z + P_\gamma^{lin}T_x\cos 2\phi)]\}
\end{aligned}
$$

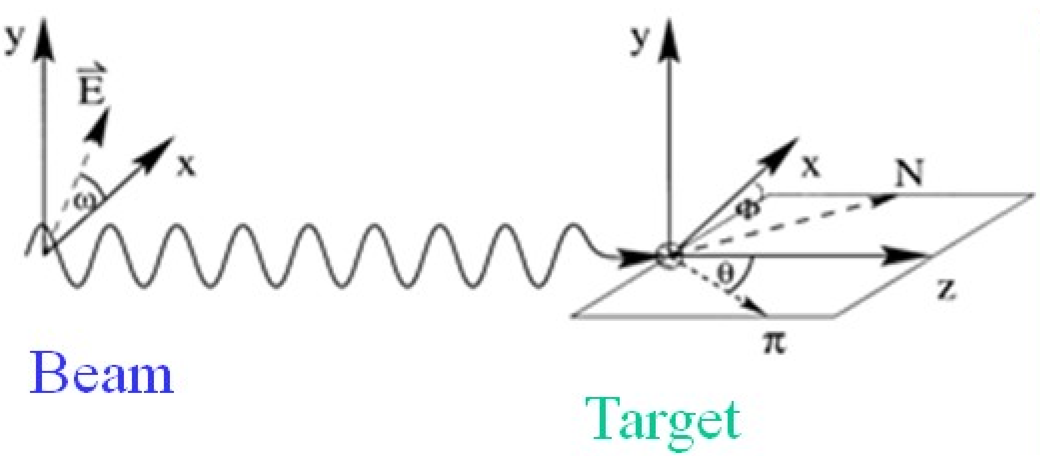
Nature and Properties of nucleon resonances

⇒ Polarization observables used to disentangle broad, overlapping resonances.

Observables in pseudoscalar meson prod.

(Barker, Donnachie & Storrow Nucl Phys B95 (1975))

$$\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{unpol}\{1 - P_\gamma^{lin}\Sigma\cos 2\phi + P_x(P_\gamma^{circ}F + P_\gamma^{lin}H\sin 2\phi)$$
$$+ P_y(T - P_\gamma^{lin}P\cos 2\phi) + P_z(P_\gamma^{circ}E + P_\gamma^{lin}G\sin 2\phi)$$
$$+ \sigma'_x[P_\gamma^{circ}C_x + P_\gamma^{lin}O_x\sin 2\phi + P_z(T_x - P_\gamma^{lin}L_z\cos 2\phi)$$



Beam / Target	γ_{unpol}	P_γ^{lin} $\left(0, \frac{\pi}{2}\right)$	P_γ^{lin} $\left(+\frac{\pi}{4}, -\frac{\pi}{4}\right)$	P_γ^{circ}
P_{unpol}	$\left(\frac{d\sigma}{d\Omega}\right)$	$\Sigma(\theta)$	-	-
P_x	-	-	$H(\theta)$	$F(\theta)$
P_y	$T(\theta)$	$P(\theta)$	-	-
P_z	-	-	$G(\theta)$	$E(\theta)$

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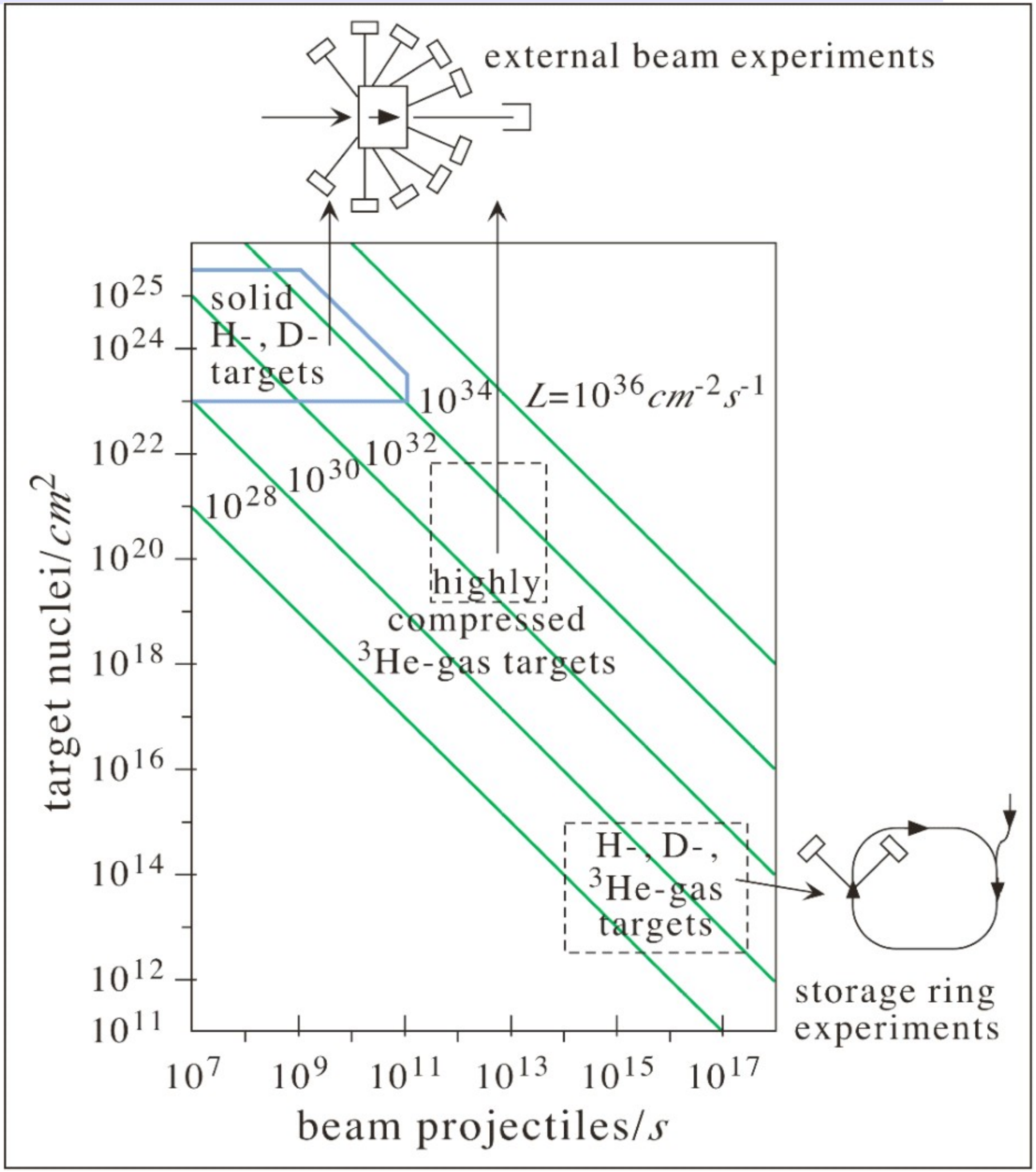
Polarized Targets and Particle Physics Experiments

Critical Parameter: reaction rate
Optimization of the
counting rate N

$$N = L \cdot \frac{d\Sigma}{d\Phi} \cdot \Delta\Phi \, [s^{-1}]$$

Luminosity L

$$L = \underbrace{I}_{\text{beam intensity}} \cdot \underbrace{n_{target}}_{\text{areal density of the target}} \, [cm^{-2} \cdot s^{-1}]$$



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Asymmetry Measurements with Polarized Targets & Beams

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$$A = \frac{1}{P_b} \cdot \frac{1}{P_t} \cdot \frac{N_{\overleftarrow{}}^{\overrightarrow{}} - N_{\overrightarrow{}}^{\overrightarrow{}}}{N_{\overleftarrow{}}^{\overrightarrow{}} + N_{\overrightarrow{}}^{\overrightarrow{}}}$$

P_b : beam polarization

P_t : target polarization

But: All polarized targets have a fraction of unpolarized material

$$\text{Def.: Dilution factor } f = \frac{\#\text{ of polarizable nucleons}}{\#\text{ of all nucleons in the target}}$$

DNP solid targets (0.1 … 0.5); HD (0.66)

f = 0.1 …. 0.3 …. 0.5 …. 0.66 …. 0.9

^3He-gas targets (0.3); internal gas targets (0.9)

$$\Rightarrow A = \frac{1}{P_b} \cdot \frac{1}{P_t} \cdot \frac{1}{f} \cdot \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

$$FOM_{target} \sim \frac{1}{\text{measuring time}} \text{ at a given } \frac{\Delta A}{A}$$

$$\boxed{FOM_{target} = L \cdot P_b^2 \cdot P_t^2 \cdot f^2}$$

optimize + $\Delta\Omega$

A2 Collaboration

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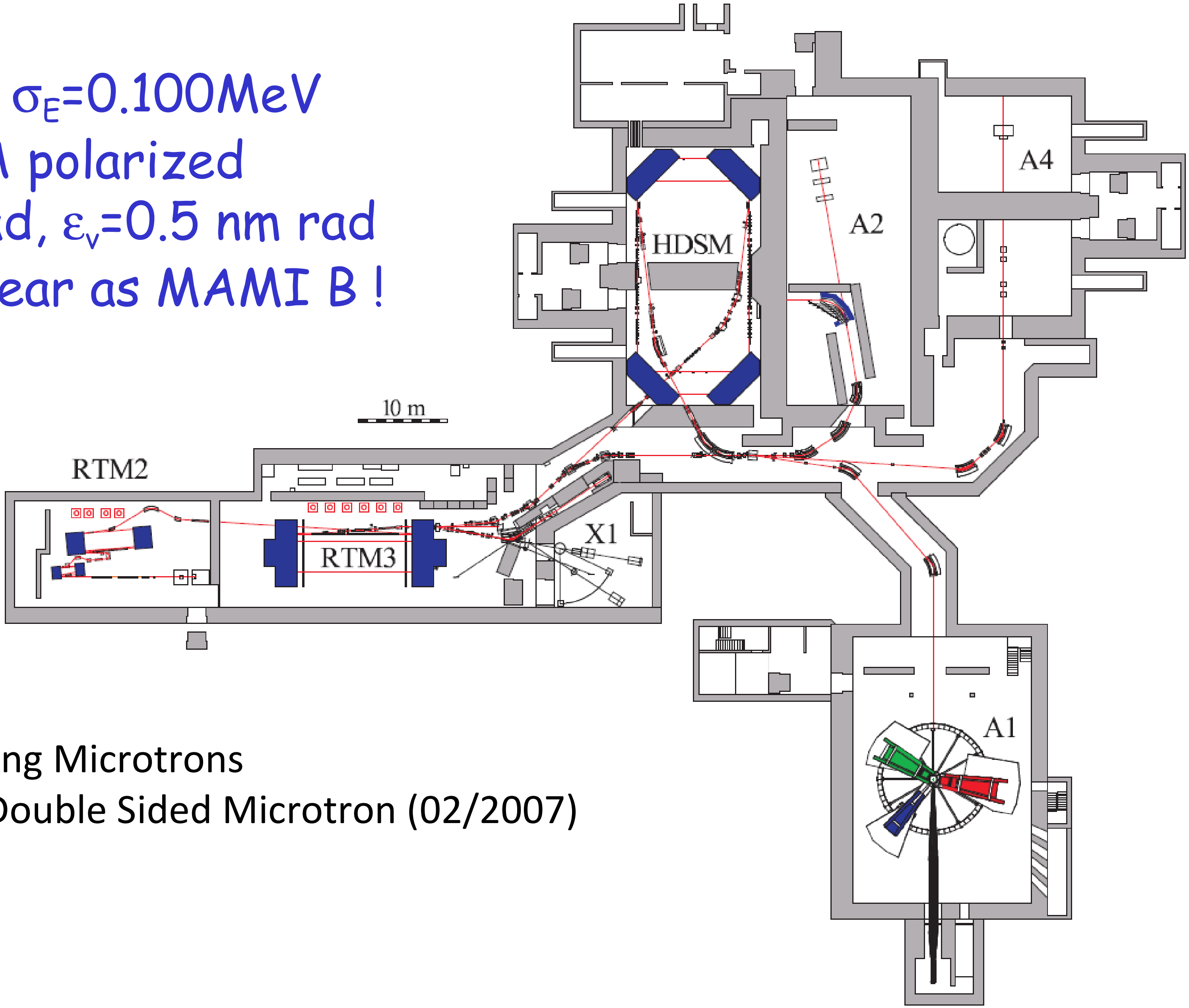
Mainz MAMI Facility

Parameter

- 1604MeV, σ_E=0.100MeV
- max. 40μA polarized
- ε_h=9 nm rad, ε_v=0.5 nm rad
- ~6500h/year as MAMI B !

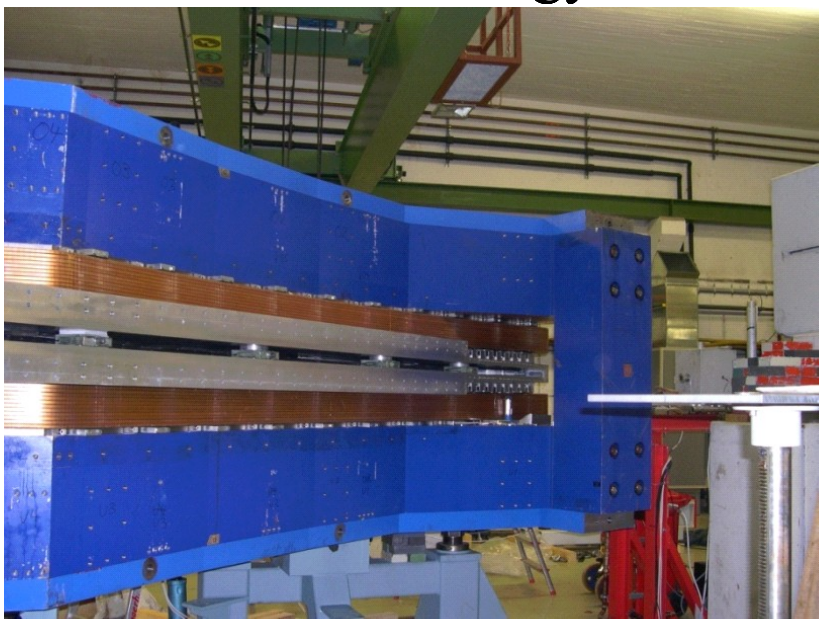


3 Race Tracking Microtrons

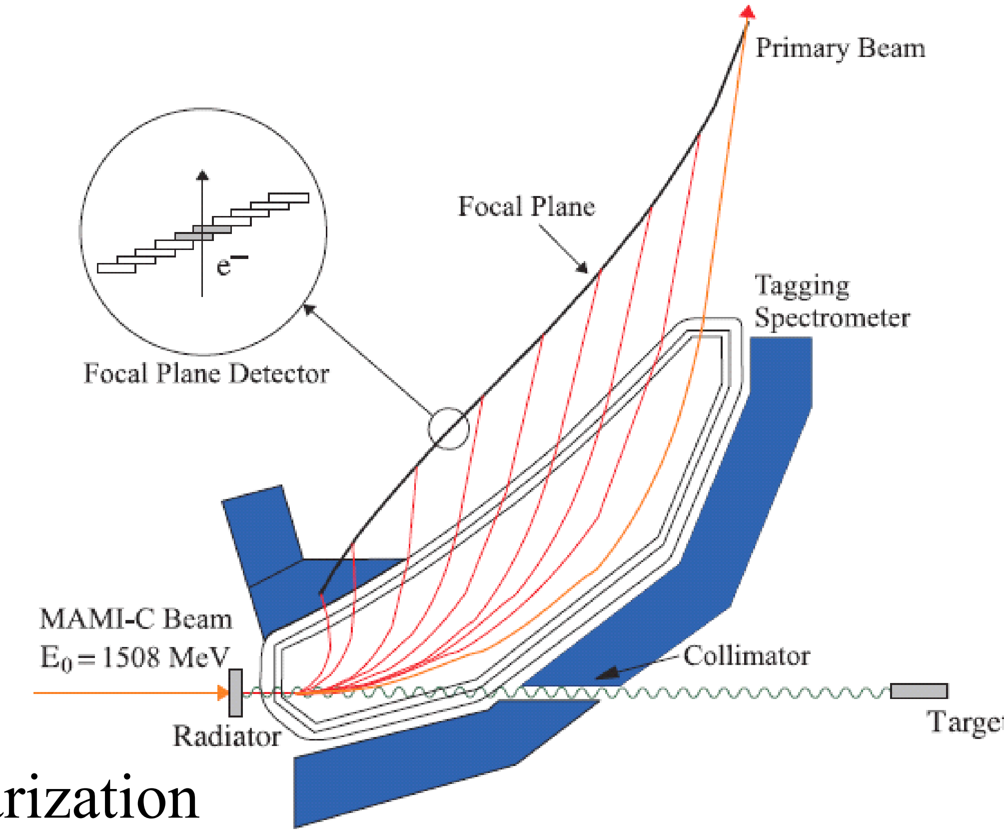
1 Harmonic Double Sided Microtron (02/2007)

Upgraded A2 Tagging system (Glasgow, Mainz)

1.Production and energy measurement of the Bremsstrahlung photons.



Glasgow Tagging Spectrometer
EPJ A 37, 129 (2008)



2.Determination of the degree of polarization the electron beam (Møller polarimeter). Circularly pol. photons.

$$A = \frac{N^+ - N^-}{N^+ + N^-} = a\vec{p}_t\vec{p}_b\cos(z)$$

3. Coherent production of linearly polarized photons on a diamond radiator

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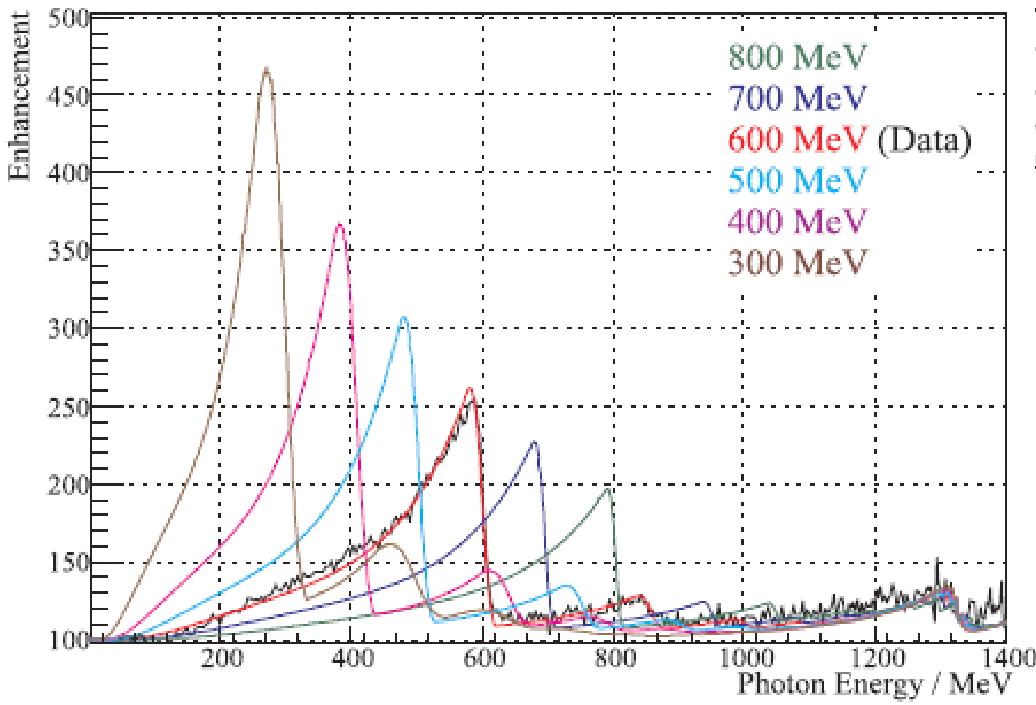
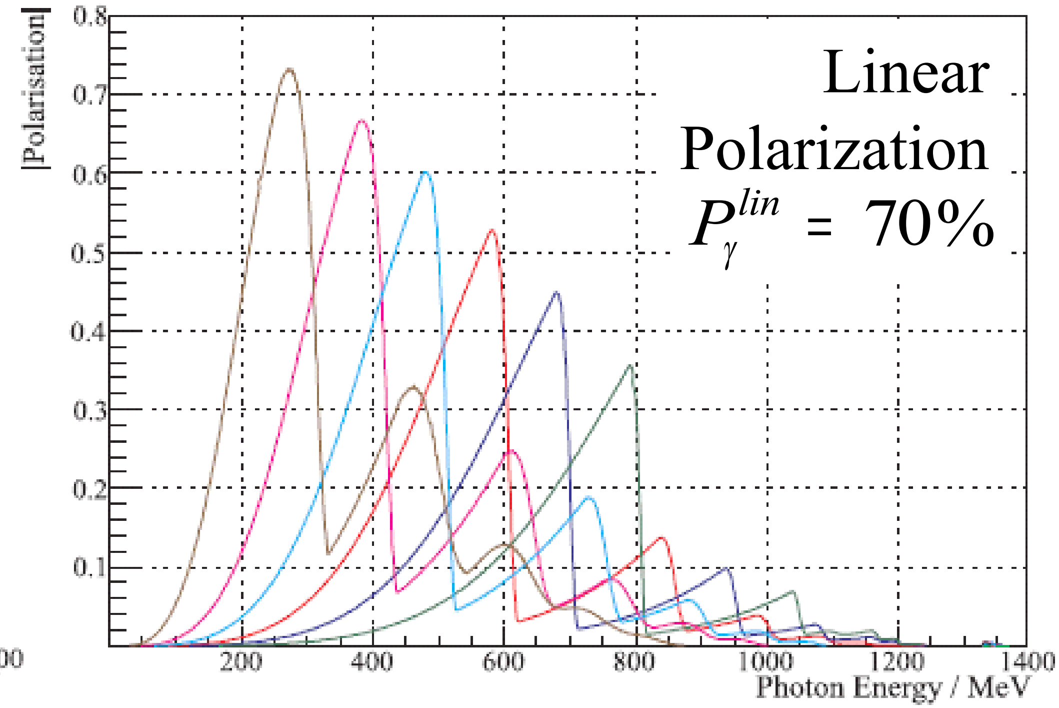
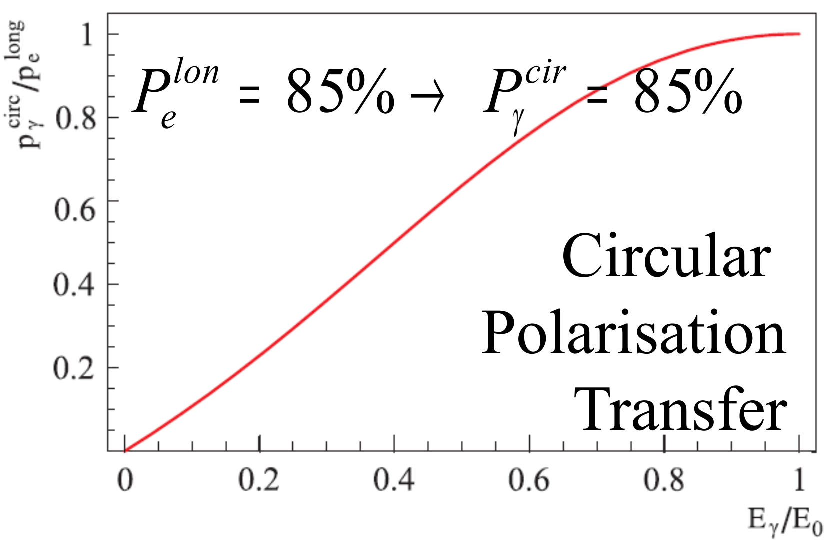
Polarized Photons @ MAMI C







E_γ = 75 ... 1480 MeV

ΔE_γ = 4 MeV

N_γ = 2 · 10^5/s/MeV

High polarization

High photon flux

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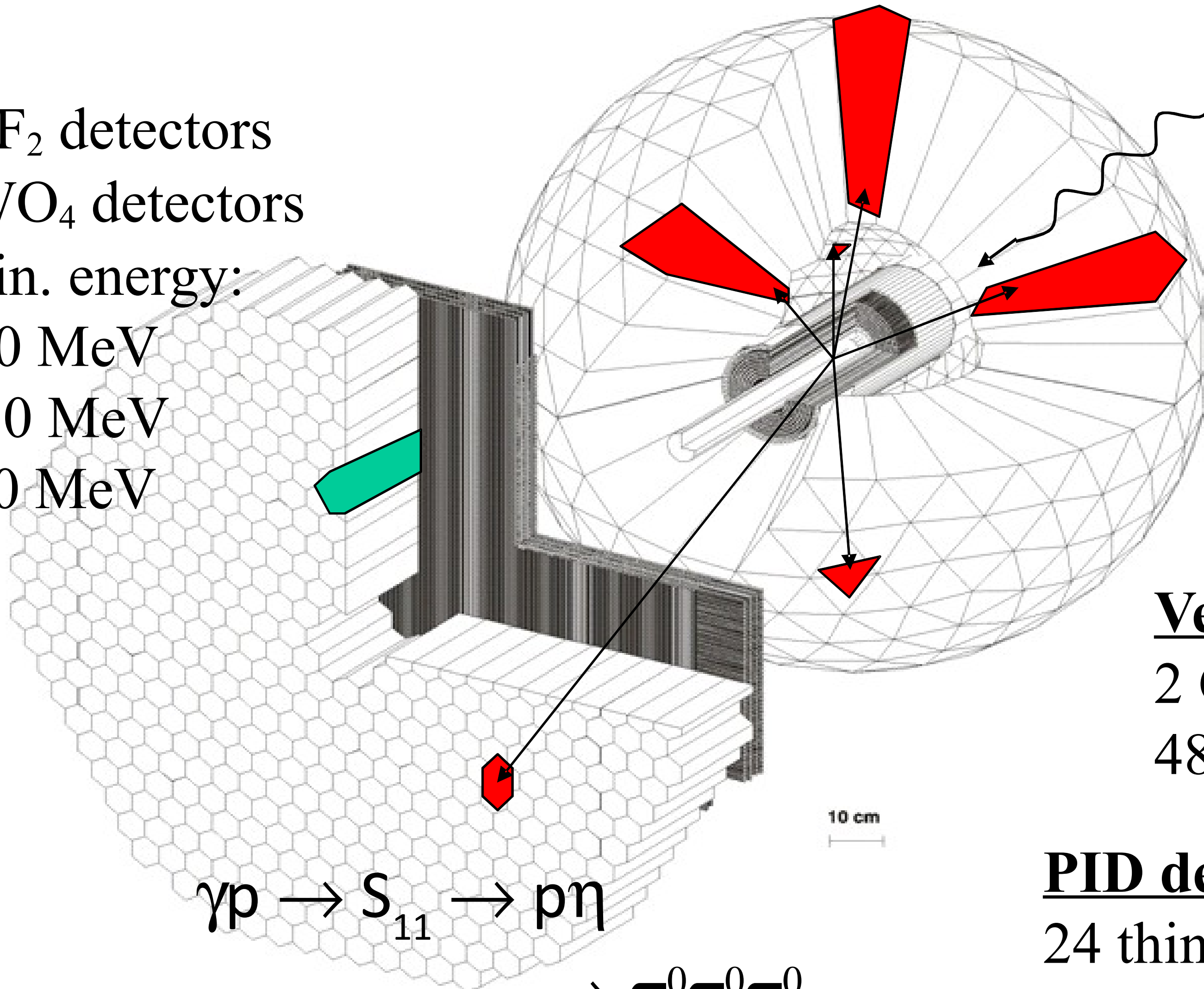
4π photon Spectrometer @ MAMI



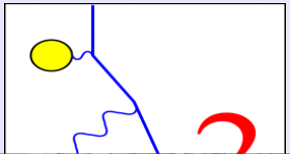
TAPS:
366 BaF_2 detectors
72 $PbWO_4$ detectors
Max. kin. energy:
π^{+-} : 180 MeV
K^{+-} : 280 MeV
P : 360 MeV

Crystal Ball:
672 NaJ detectors
Max. kin. energy:
μ^{+-} : 233MeV
π^{+-} : 240 MeV
K^{+-} : 341 MeV
P : 425 MeV

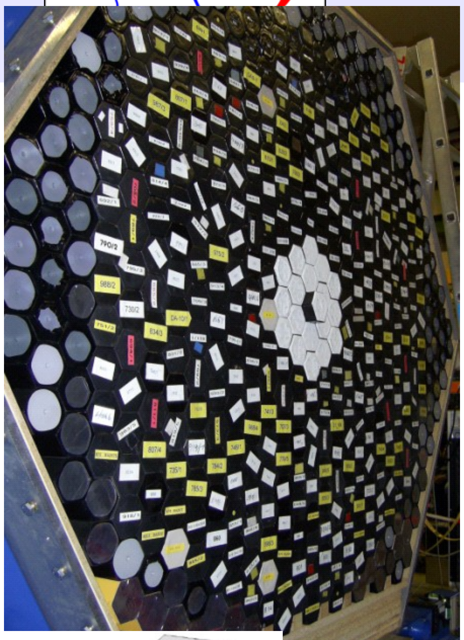
Vertex detector:
2 Cylindr. MWPCs
480 wires, 320stripes

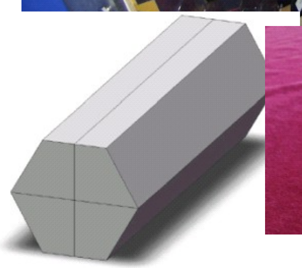
PID detector:
24 thin plastic detectors

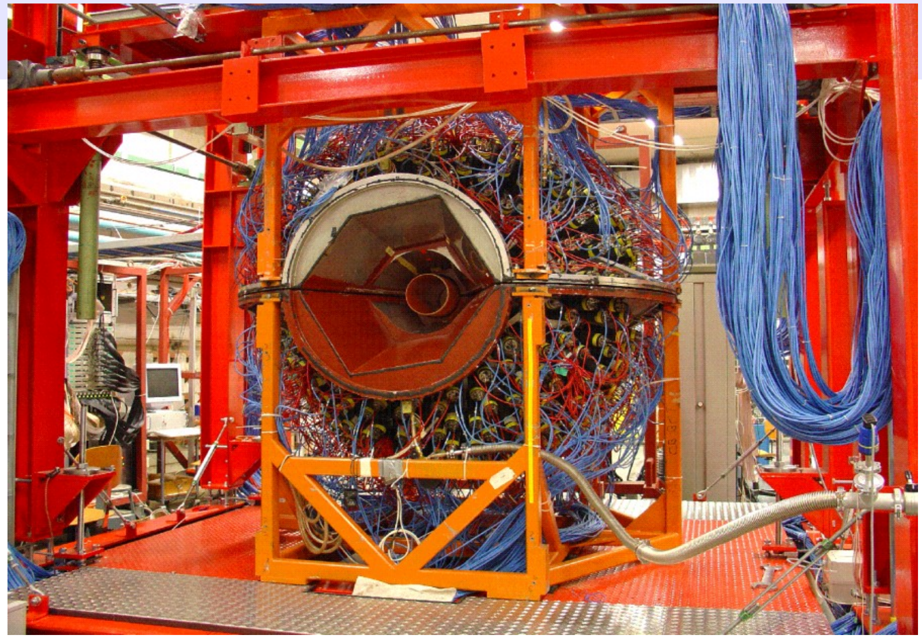
$$\gamma p \rightarrow S_{11} \rightarrow p\eta$$
$$\rightarrow \pi^0\pi^0\pi^0$$
$$\rightarrow \gamma\gamma\gamma\gamma\gamma\gamma$$

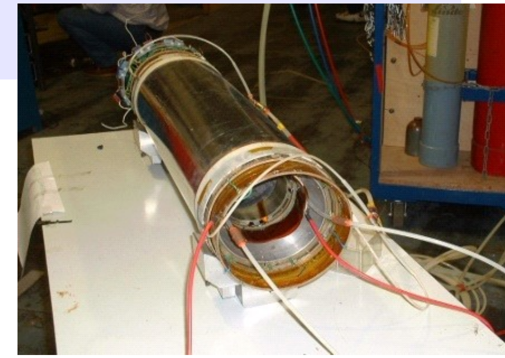


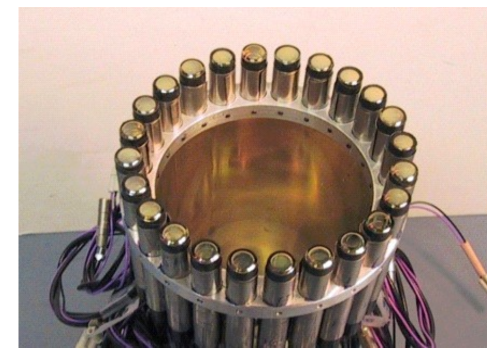
Detector











TAPS (Gießen,Basel,Mz):

- 366 BaF_2 crystals
  72 PbWo inner det.
  ($1-20^{o}$)
- Individual charged particle vetos

Crystal Ball (UCLA):

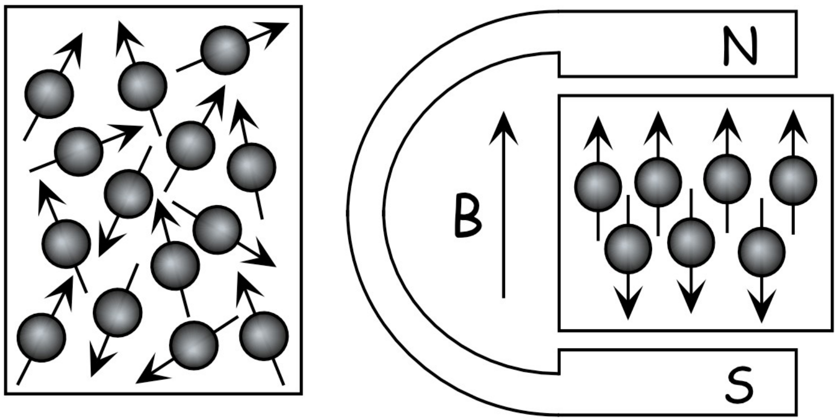
672 NaI scintillators
($20-160^{o}$)

PID and tracking:

- Barrel of 24 plastic scintillators (Edinburgh)
- MWPC (Pavia)
- Carbon analyzer for nucleon recoil polarimetry

Nucleon Polarization

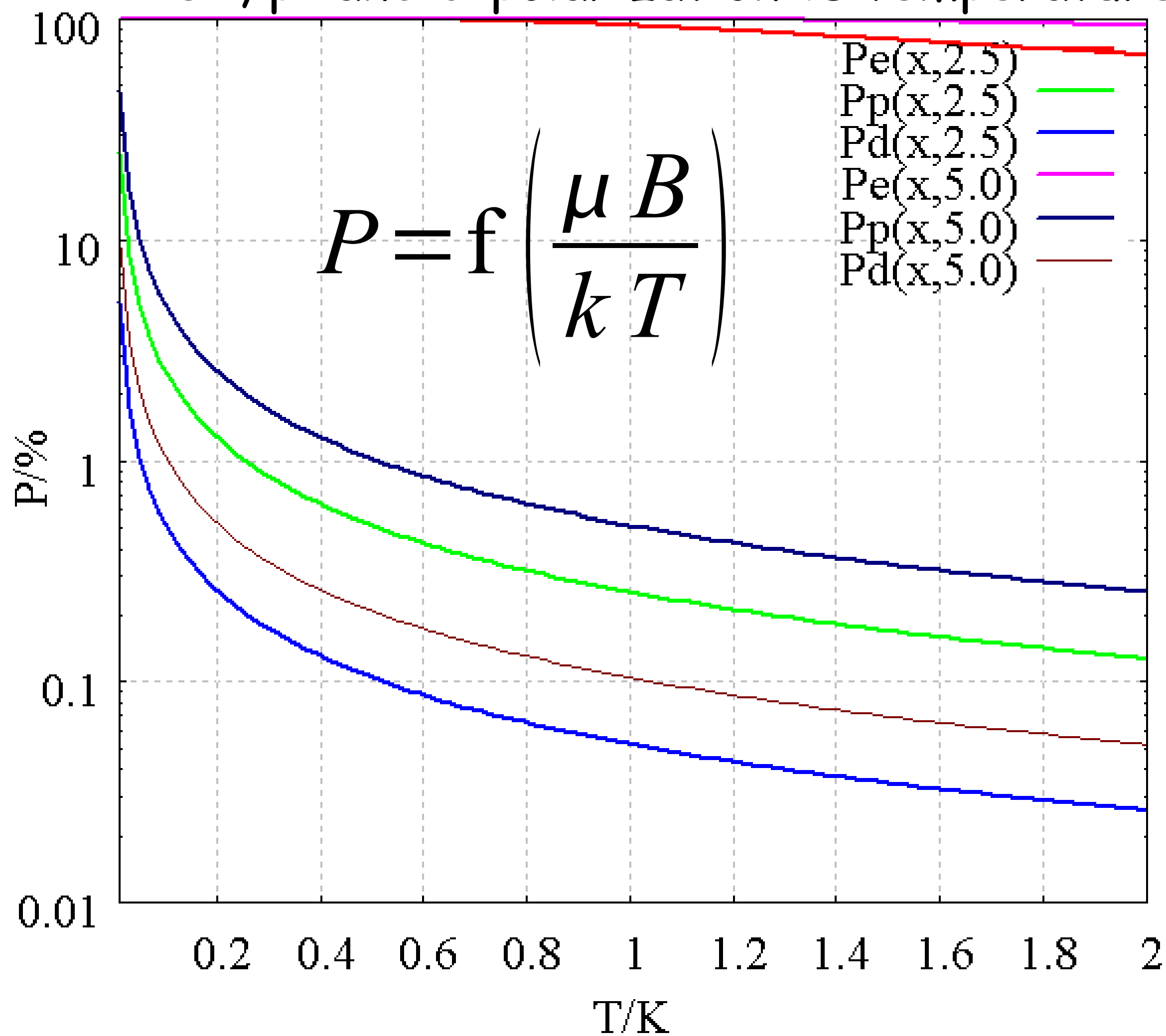
Polarization = Orientation of Spins in a magnetic field



$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

T=1K	B=2.5 T	B=5T
electron	93.3 %	99.8 %
proton	0.255 %	0.512 %
deuteron	0.052 %	0.105 %

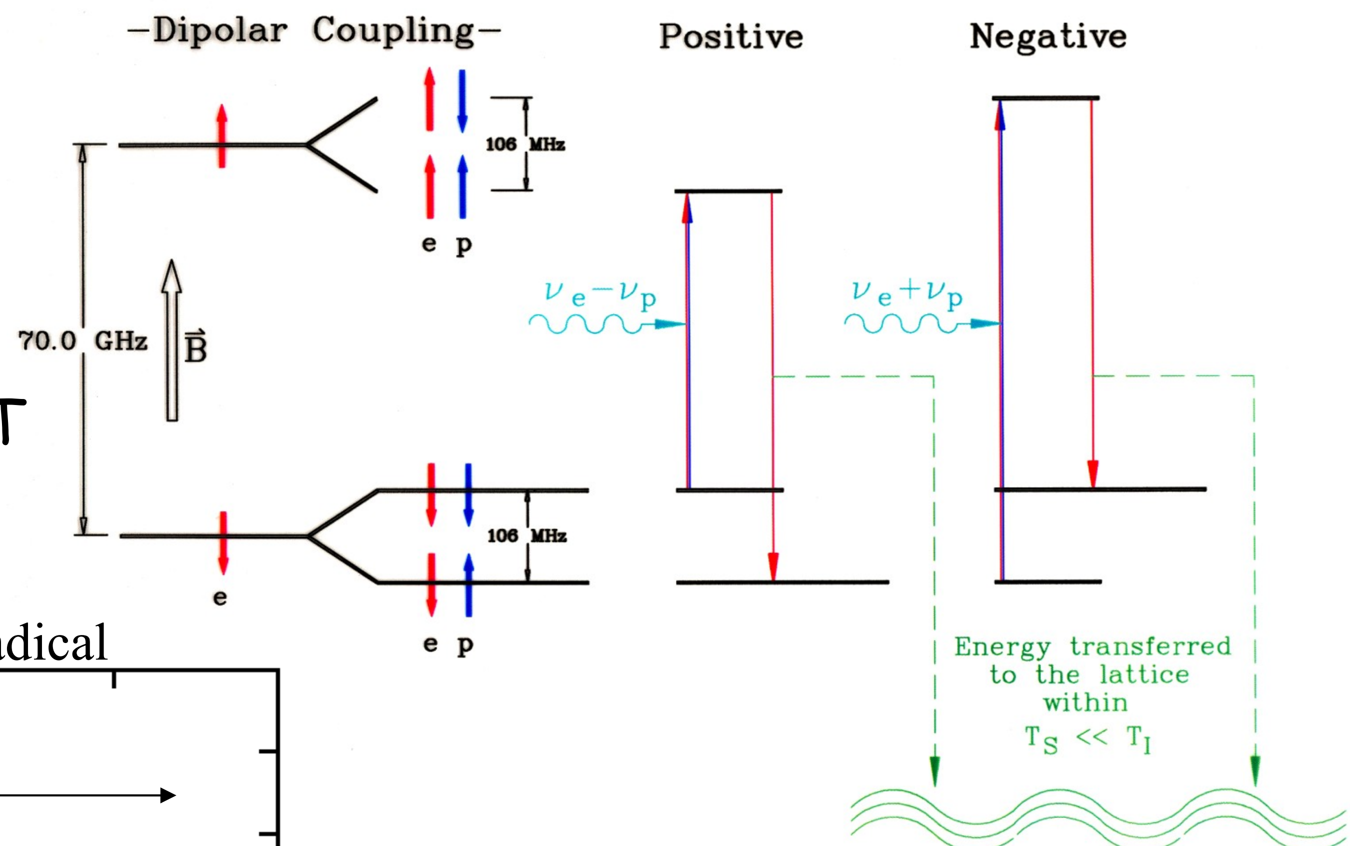
e⁻-, p- and d-polarization vs temperature



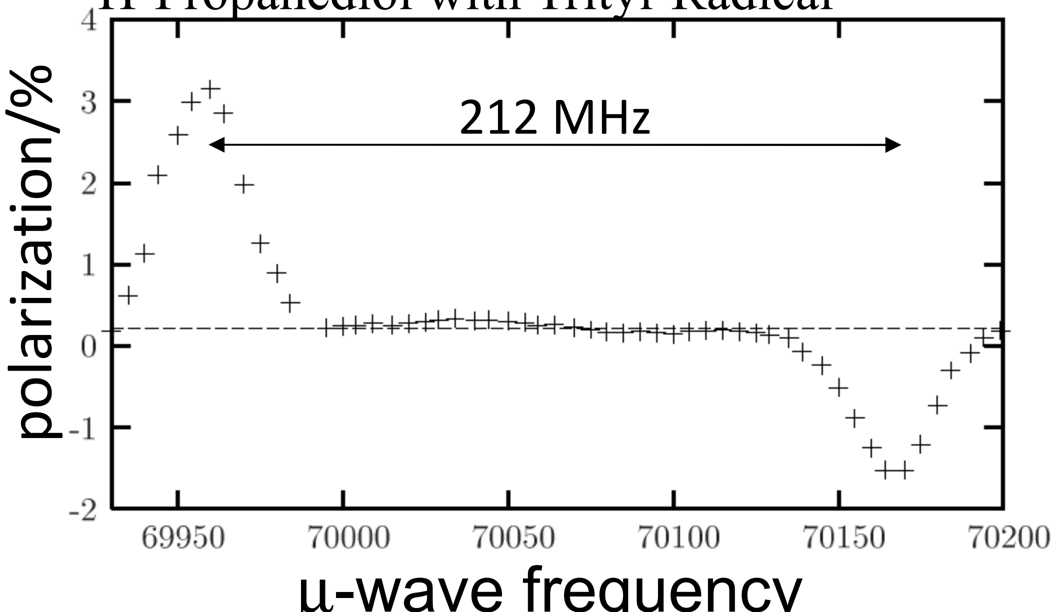
DNP: Solid State Effect (simple)

Idea: Transfer the high $P(e^-)$ to nucleon

B = 2.5T



H-Propanediol with Trityl-Radical



B = 2.5T and T=1K

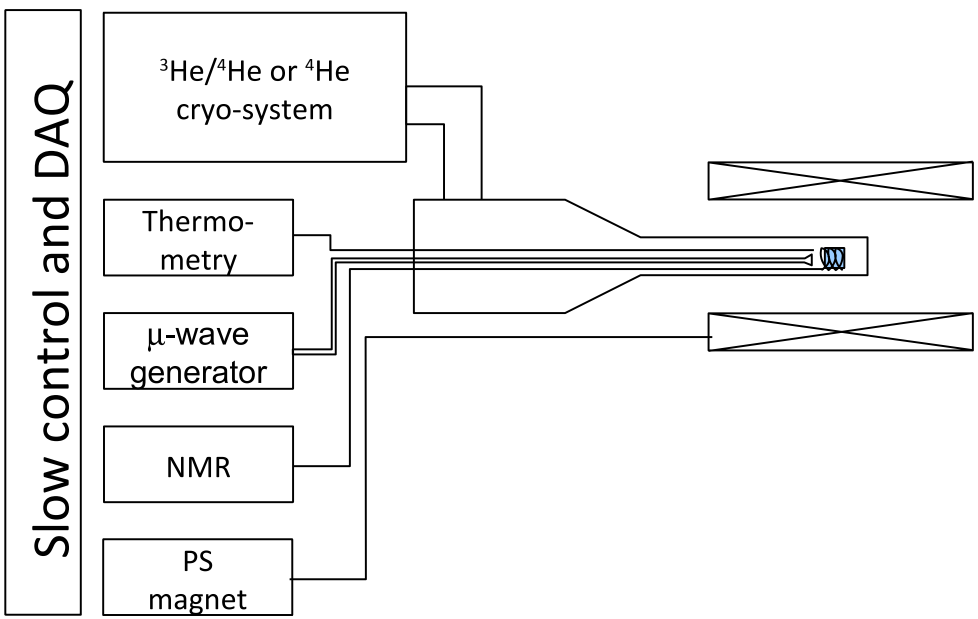
T_1^{e-} = ms to sec

T_1^{p} = min to hours

Polarized Target

- High magnetic field
- Low temperature: cryo - system
- Microwave system $\rightarrow$ DNP
- Nuclear Magnetic Resonance $\rightarrow$ polarization detection
- Target material with high content of polarizable nucleus and free e^-

$$P = f\left(\frac{\mu B}{k T}\right)$$

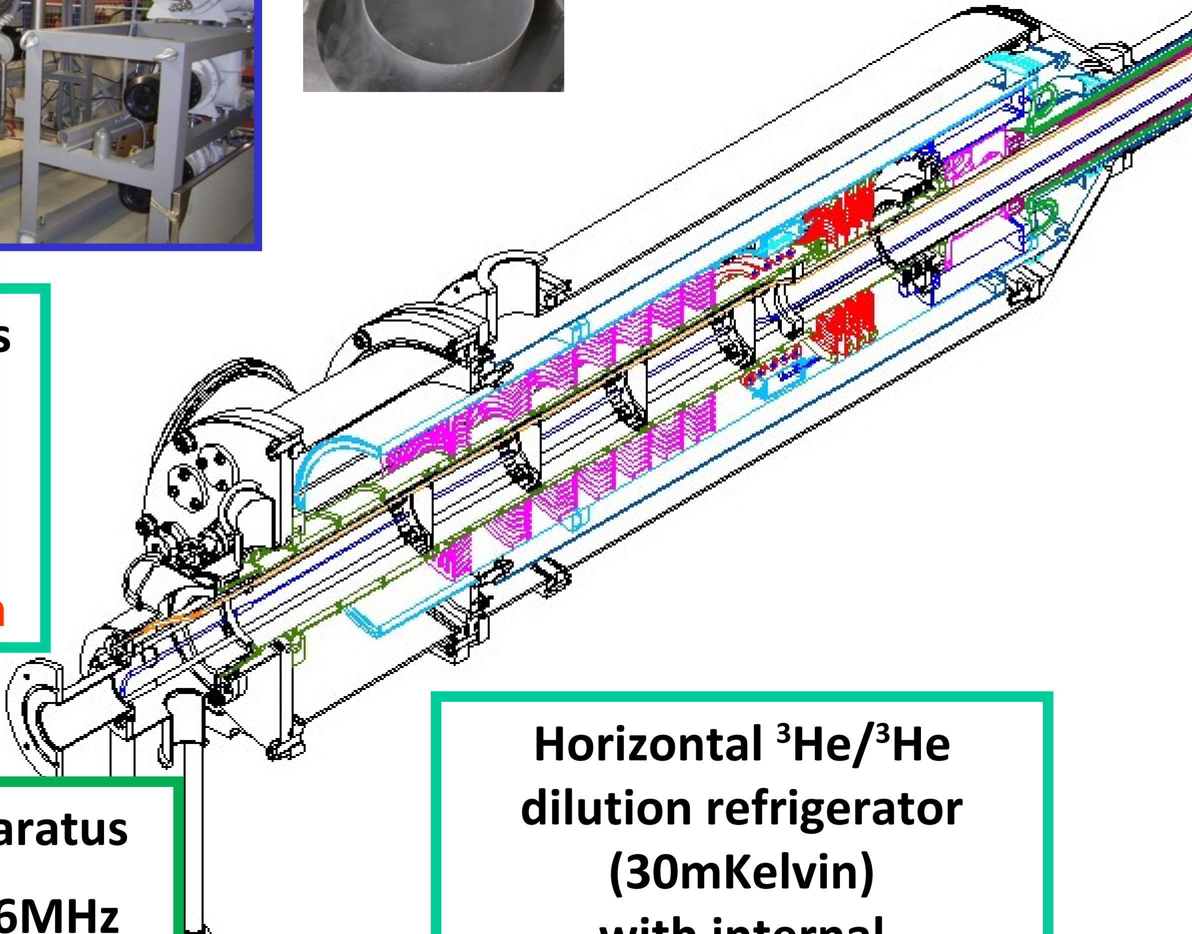


- T : 1K – 50 mK
- B : 2.5 – 5 T
- μ-w. : 70 – 140 GHz
- NMR RF
  - D : 16 – 32 MHz
  - P : 106 – 212 MHz

PT for the Crystal Ball detector

$^3He/^4He$ Roots
$4000m^3/h$
Vacuum system

Targetmaterial
[Meyer, Bochum]
H-Butanol, D-Butanol



Microwaves
70GHz
Dynamic
Nuclear
Polarization

NMR - Apparatus
106MHz, 16MHz
polarization meas.

Horizontal $^3He/^3He$
dilution refrigerator
(30mKelvin)
with internal
holding coil

Superconducting
polarization magnet
5Tesla

Polarized Target for Crystal Ball

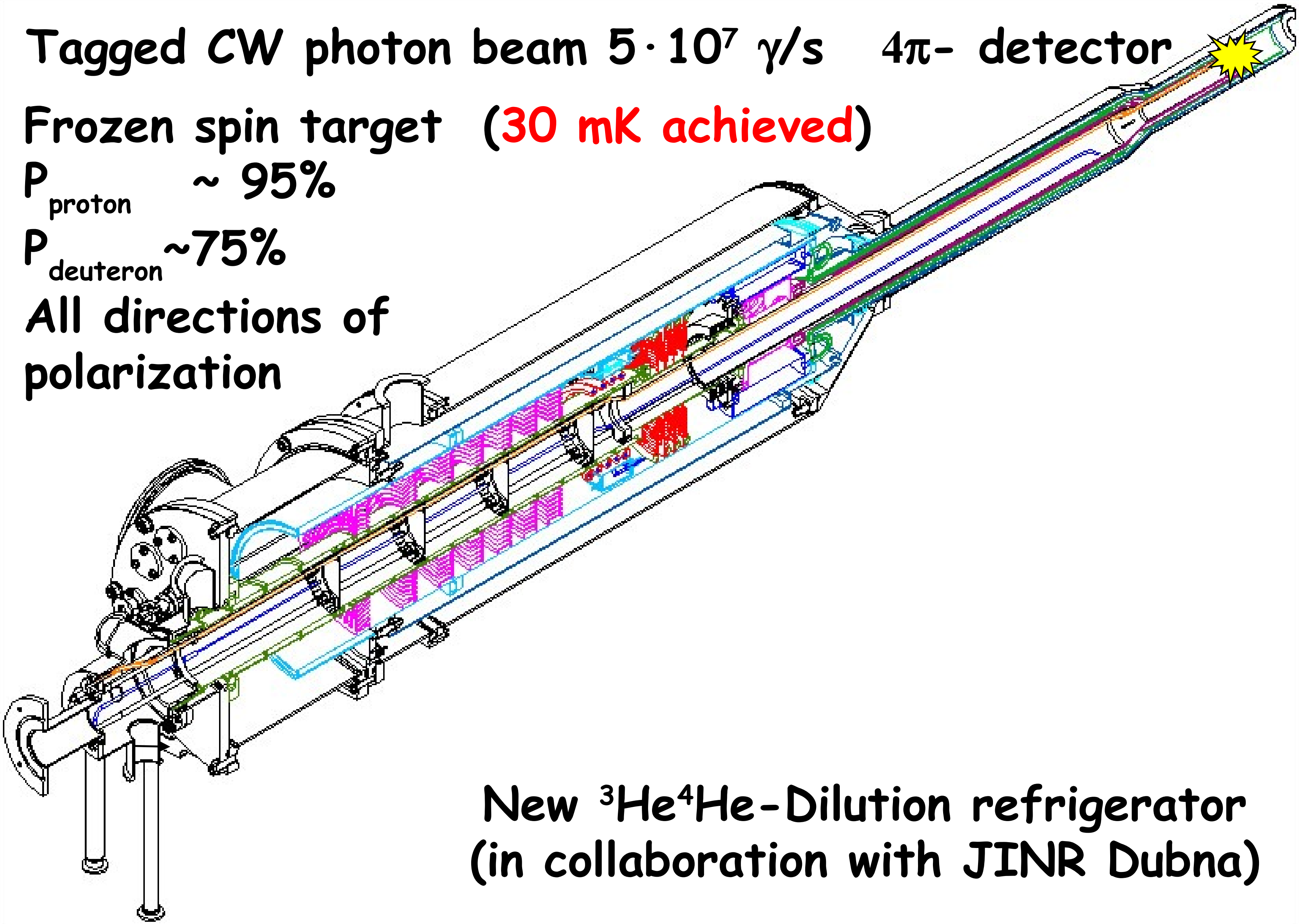
Tagged CW photon beam $5 \cdot 10^{7}$ γ/s 4π- detector

Frozen spin target (30 mK achieved)

P_{proton} ~ 95%

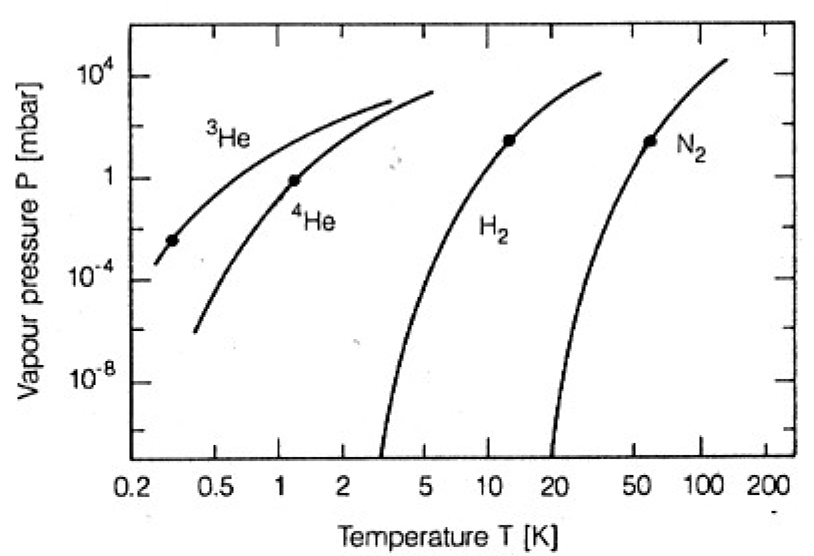
$P_{deuteron}$ ~75%

All directions of polarization



New $^{3}He^{4}He$-Dilution refrigerator (in collaboration with JINR Dubna)

Cryogenics



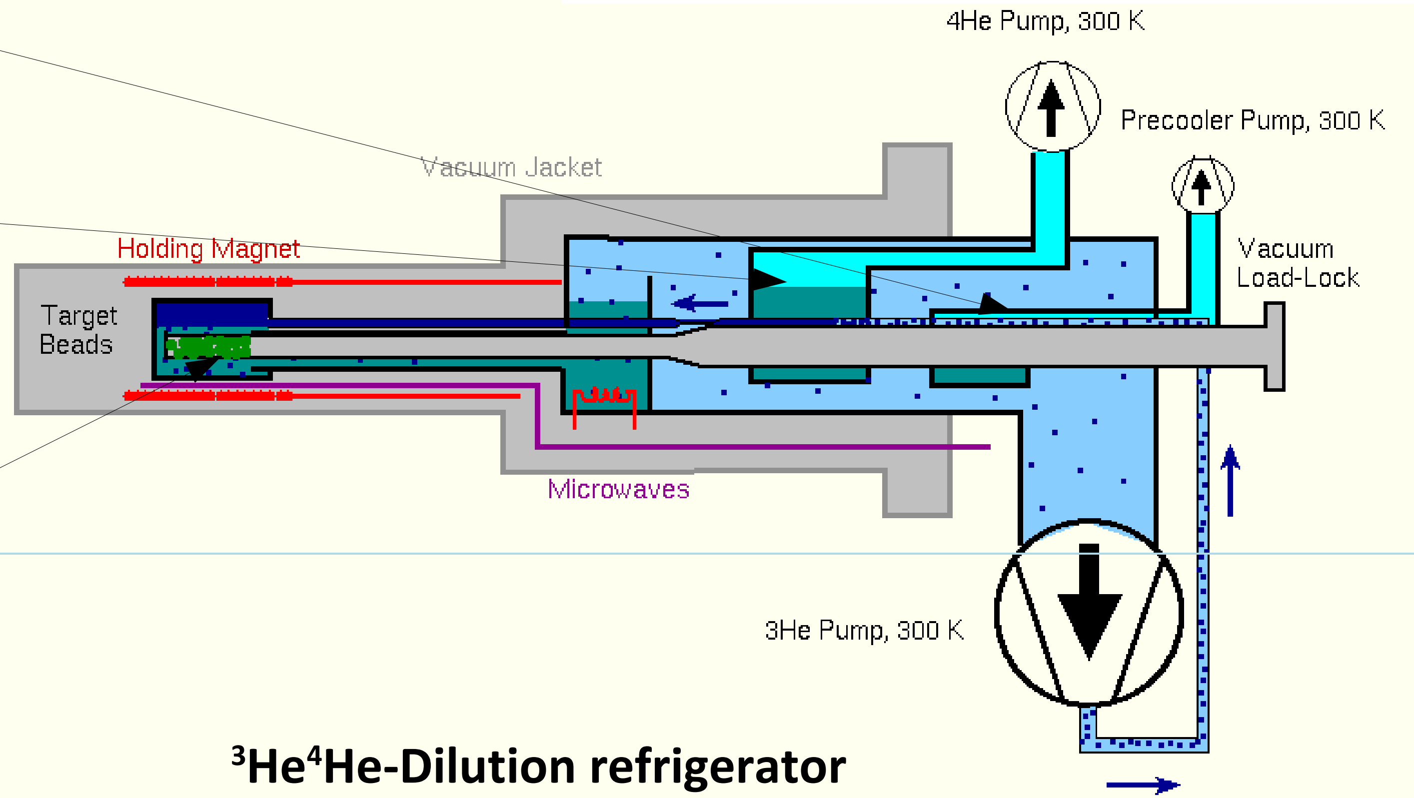
Evaporation cooling

2 Precooling stages:

Separator (4.2Kelvin pot)

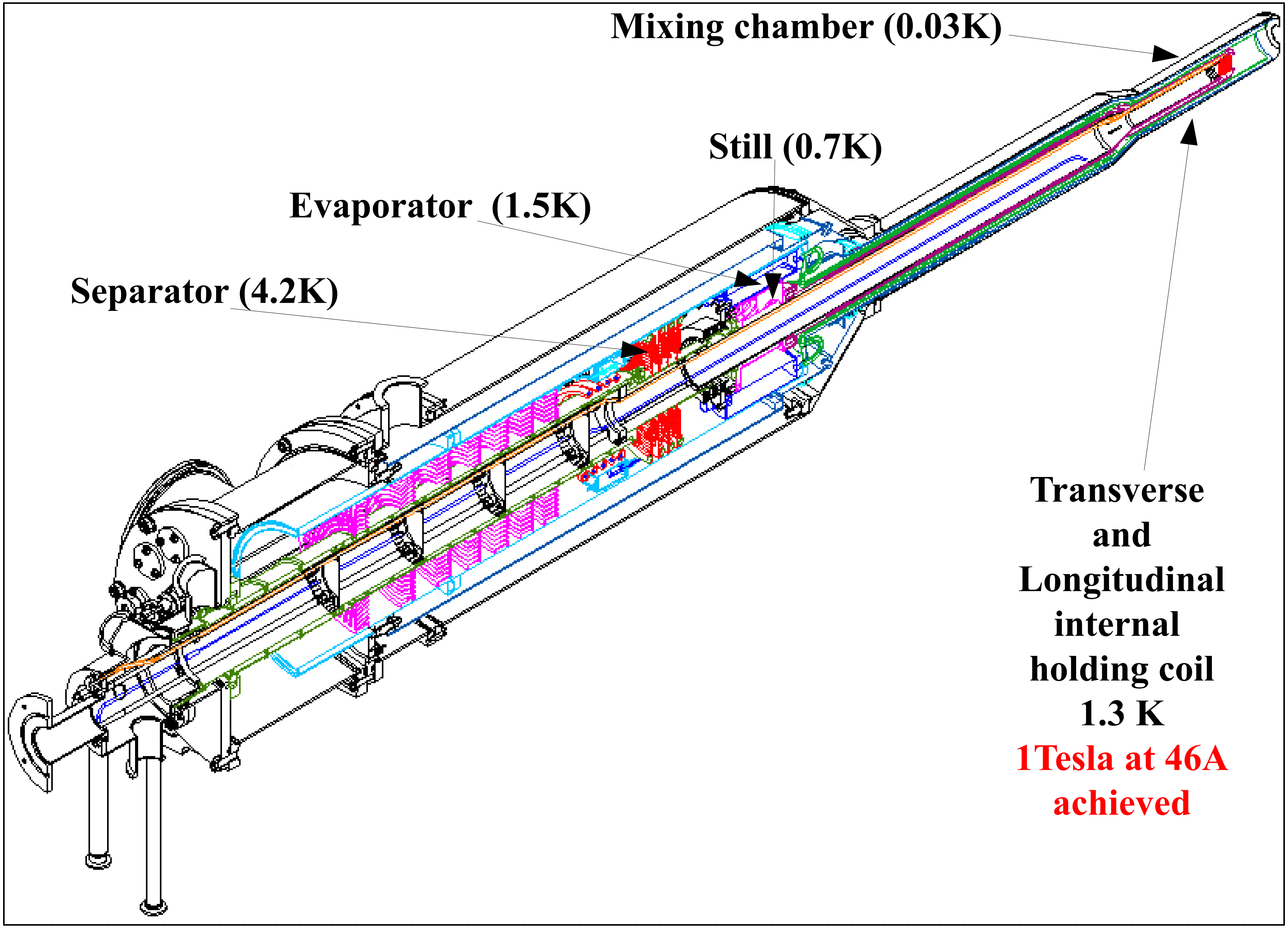
Evaporator (1.5Kelvin)

Dilution circuit (0.03Kelvin



$^3He^4He$-Dilution refrigerator

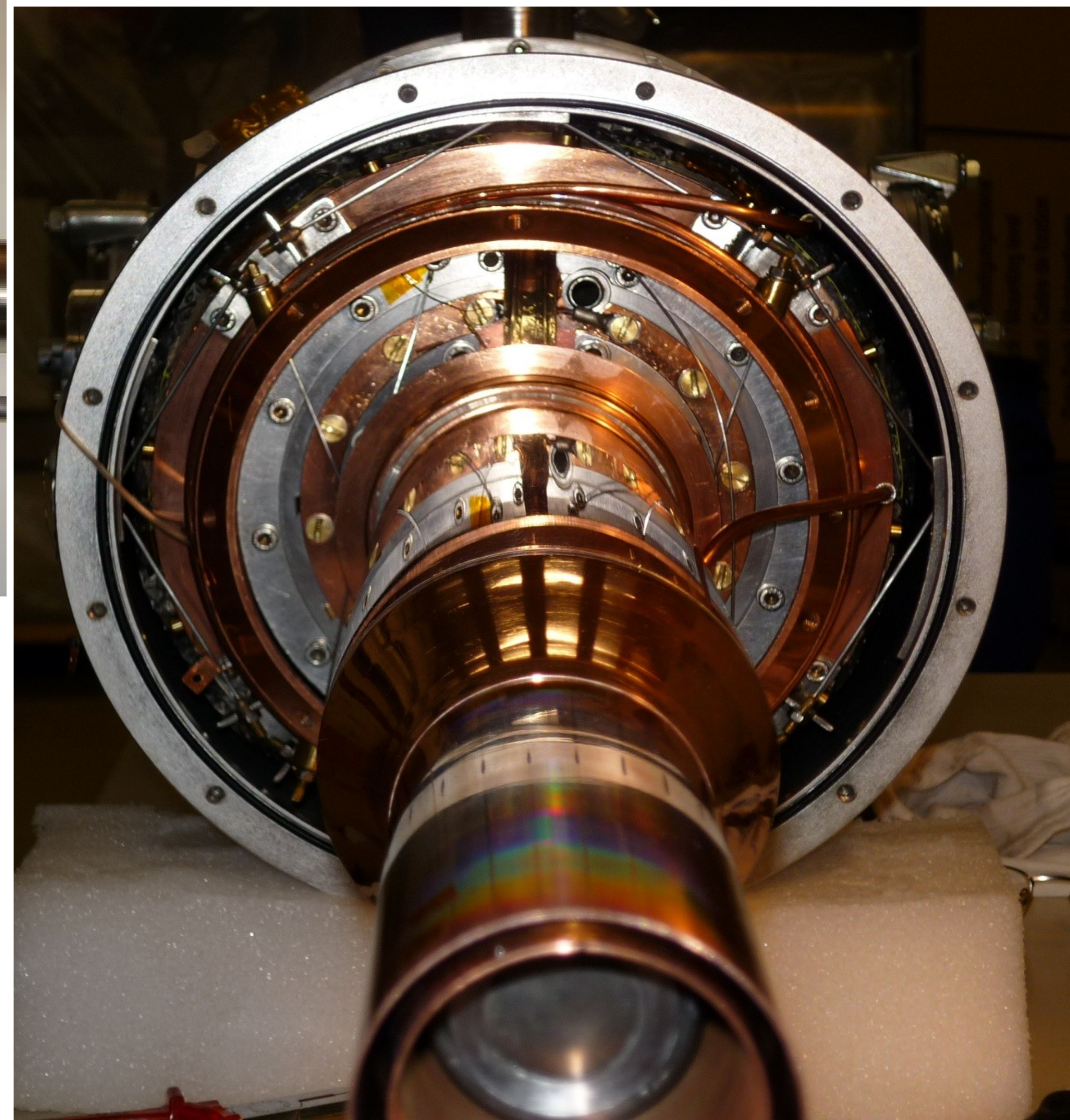
Mainz/Dubna Dilution refrigerator



Impressions from the technical realization

High temperature heat exchanger

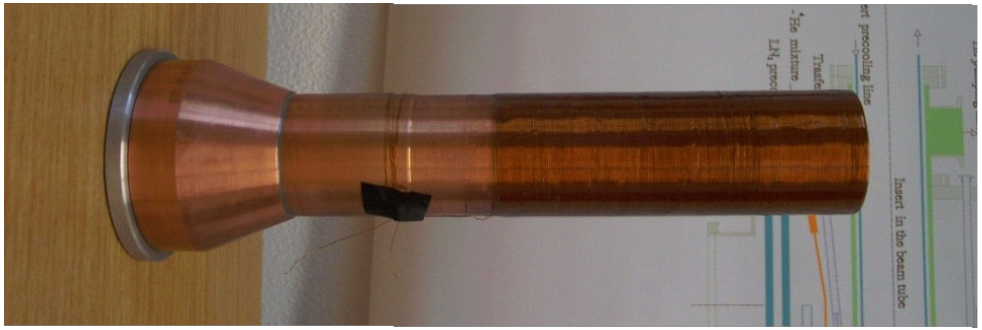
Alignment thermal radiation shields



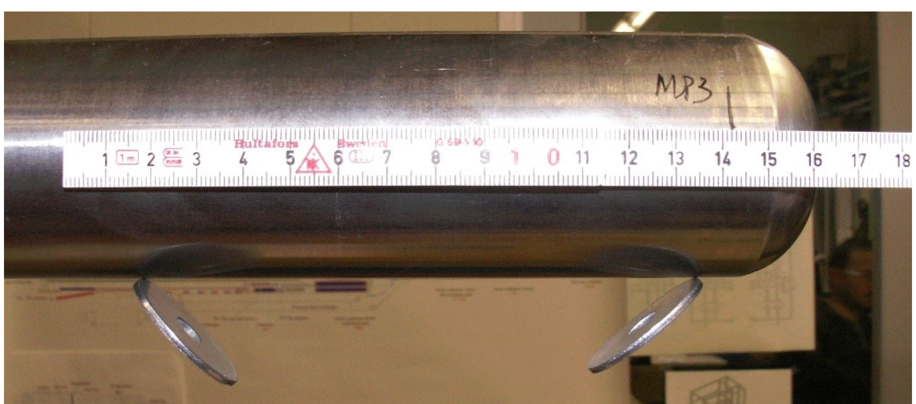
Alignment still and evaporator

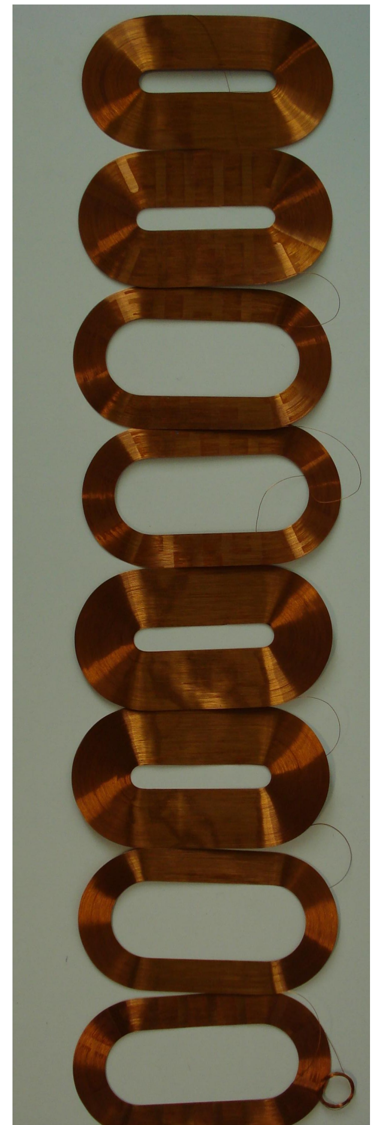
Collaboration

Holding coils for longitudinal and transverse polarization



Coil winding by TBM Mainz
(Herr Kappel)
Glueing by TBV Mainz
(Herr Kauth)



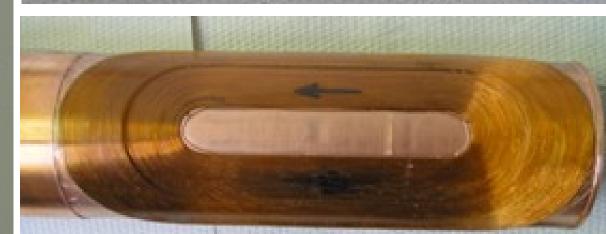


B_{trans}=0.5T
B_{long}=1.0T

4-layer dipole:

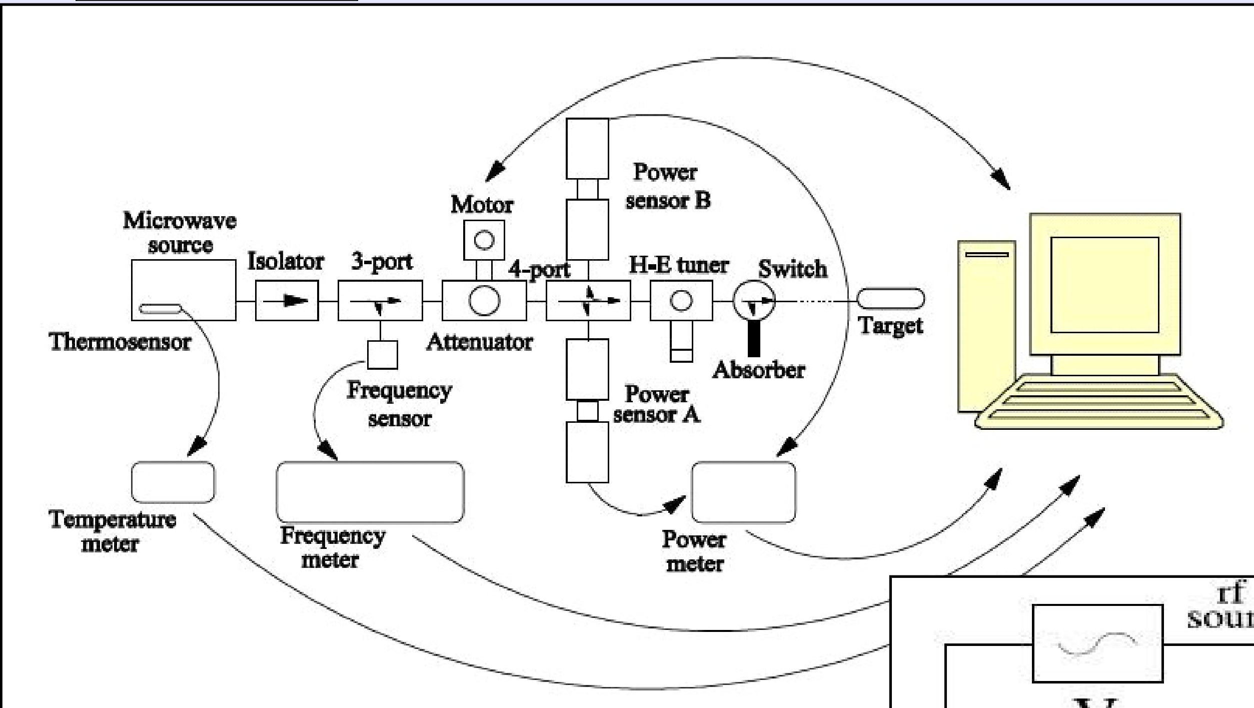
N1=N2=138

N3=N4=78



150mm

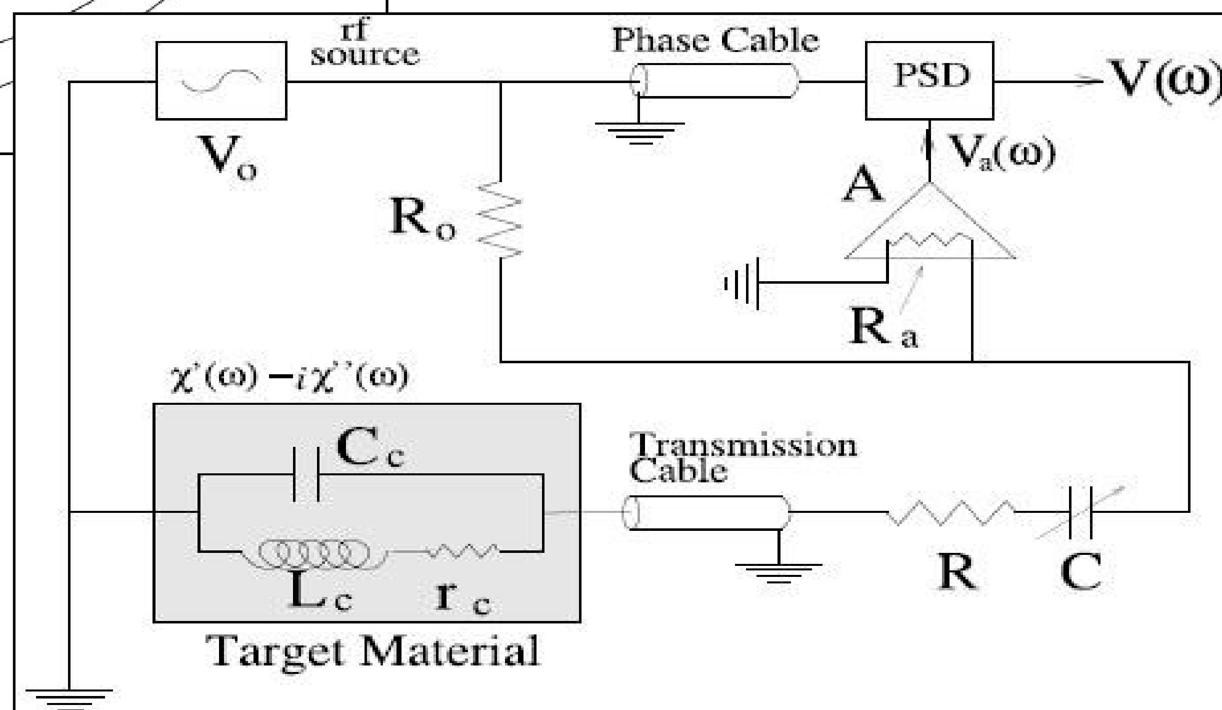
μ-Wave and NMR-System



<u>Microwave system</u>

70 GHz

Diploma Martinez 2003



<u>NMR system</u>

106 MHz

Diploma Frömmgen 2009

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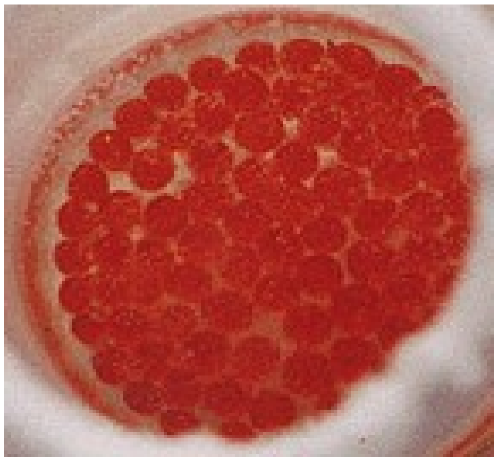
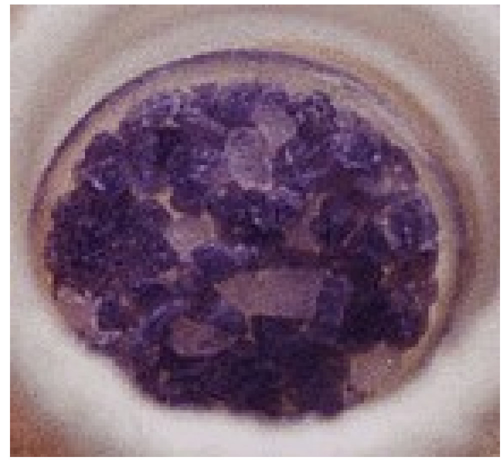
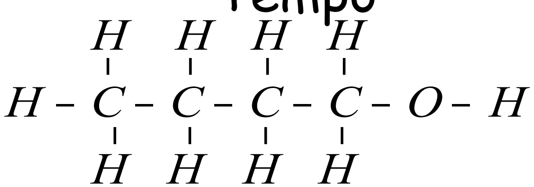
Target material

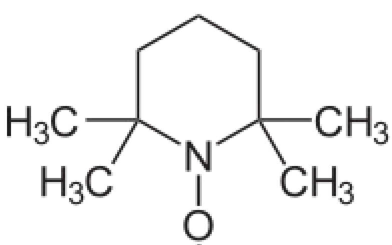
High content of polarizable nucleons with $10^{-4} e^{-}/n$ chemically doped or irradiated



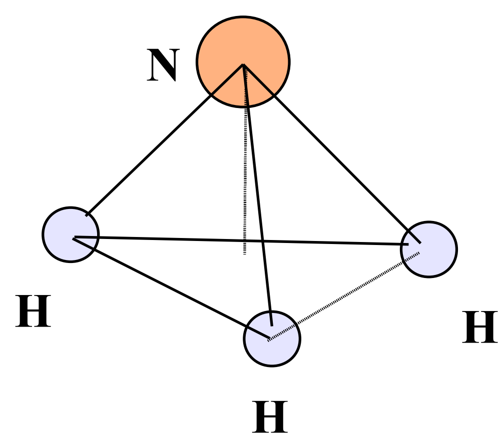


Butanol with Tempo

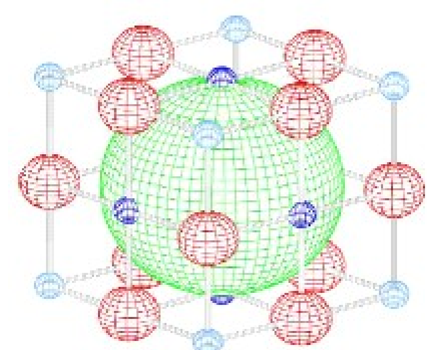




Ammonia irradiated



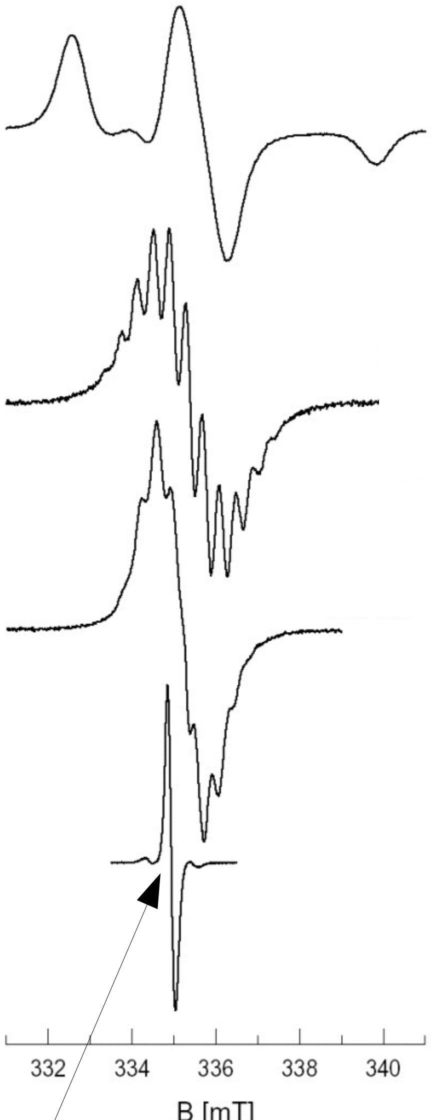
LiD irradiated



EPR spectra of dif. radicals in D-Butanol

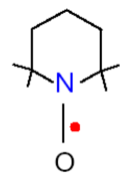
B=0.33 T

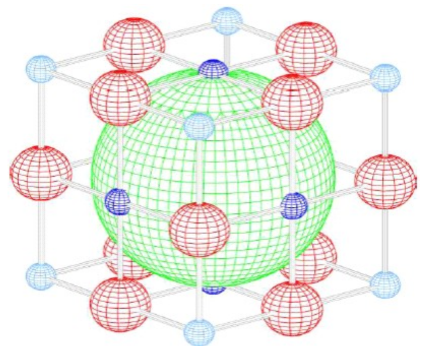
B=2.5 T



Width ≈ 0,22 mT

TEMPO

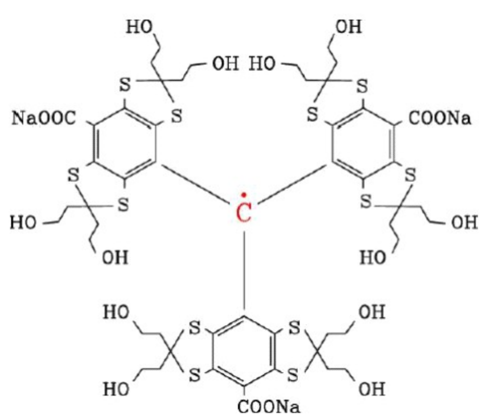


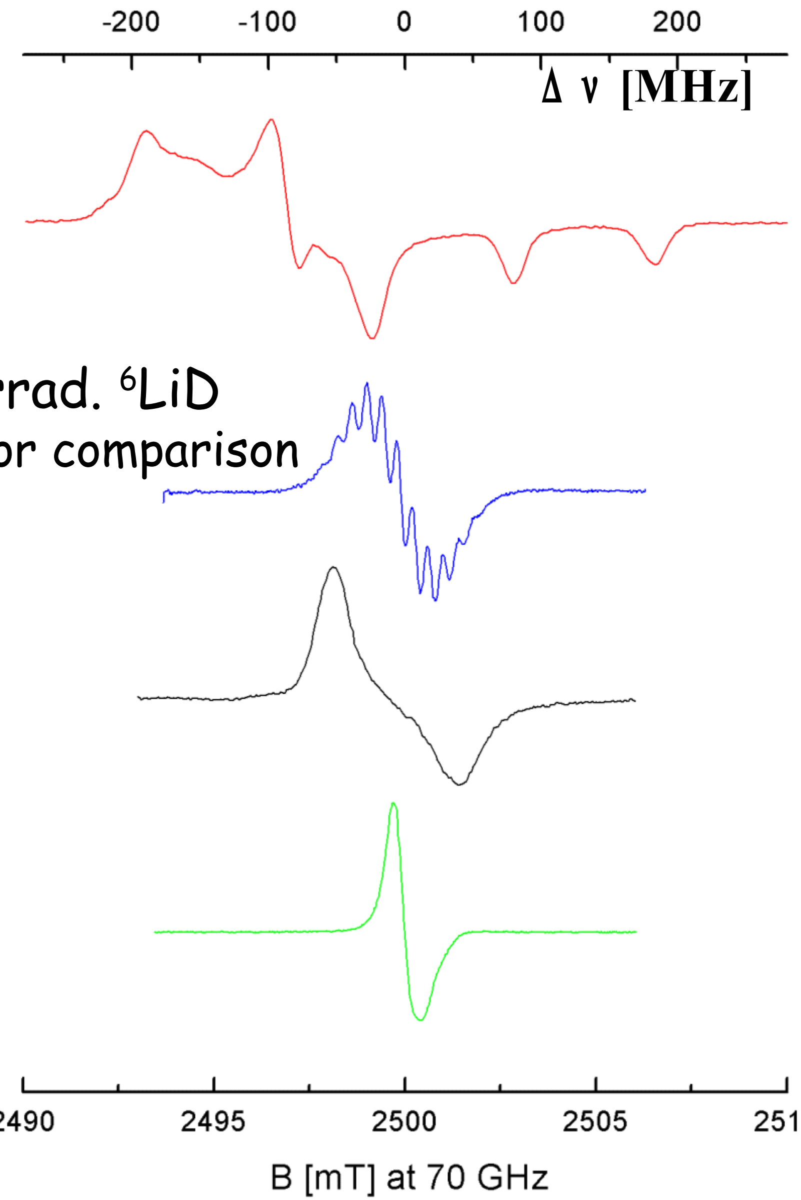


irrad. ^{6}LiD
for comparison

irrad. $(C_4D_8)OD$

trityl





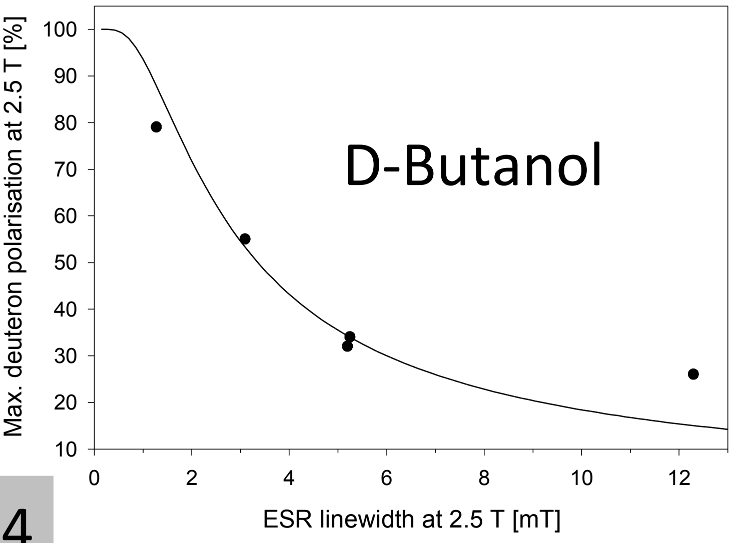
EPR line width and P_{max}

Material	Radikal	$\Delta g/\bar{g}$ $[10^{-3}]$	FWHM $[mT]$	$P_{D,max}$ [%]
D-Butanol	EDBA	5.98 ± 0.03	12.30 ± 0.20	26
D-Butanol	TEMPO	3.61 ± 0.13	5.25 ± 0.15	34
D-Butanol	Porphyrexid	4.01 ± 0.15	5.20 ± 0.23	32
$^{14}ND_3$	$^{14}\dot{N}D_2$	$\approx 2 \ldots 3$	4.80 ± 0.20	44
$^{15}ND_3$	$^{15}\dot{N}D_2$	$\approx 2 \ldots 3$	3.95 ± 0.15	-
D-Butanol	Hydroxyalkyl	1.25 ± 0.04	3.10 ± 0.20	55
^{6}LiD	F-Zentrum	0.0	1.80 ± 0.01	57
D-Butanol	Finland D36	0.50 ± 0.01	1.28 ± 0.03	79
D-Propandiol	Finland H36	0.47 ± 0.01	0.97 ± 0.04	-
D-Propandiol	OX063	0.28 ± 0.01	0.86 ± 0.03	81

Spin temperature theory

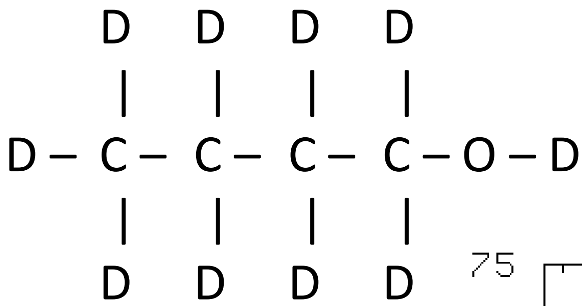
$$P_{I,max} = B_I \left(I \frac{\hbar \omega_0}{2kT_L} \frac{\omega_I}{D} \frac{1}{\sqrt{\delta(1+f)}} \right)$$

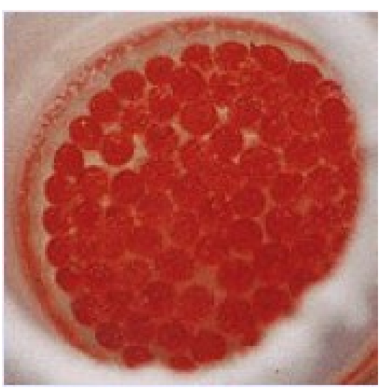
D EPR line width



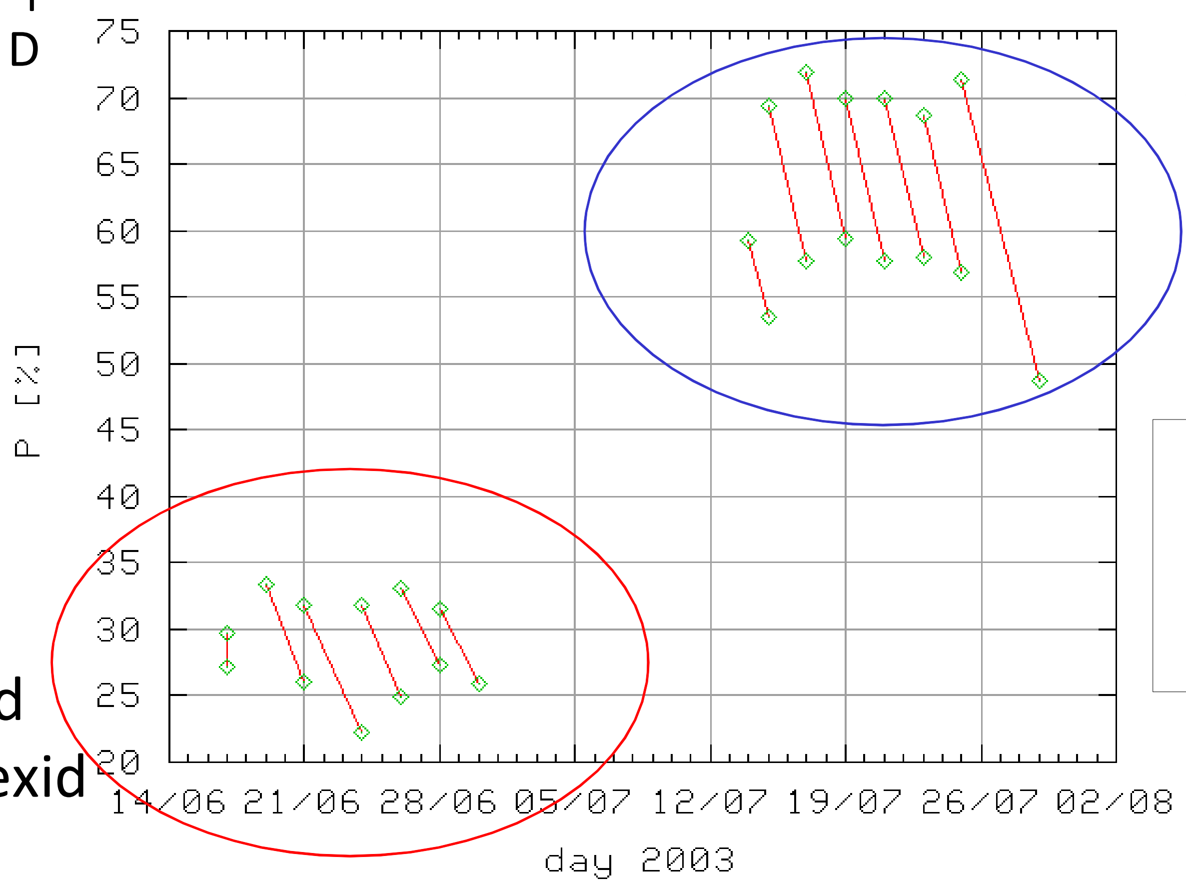
Thesis: Jörg Heckmann 2004
Habil: Stefan Goertz 2002

D-Butanol GDH Mainz 2003





Butanol doped with porphyrexid



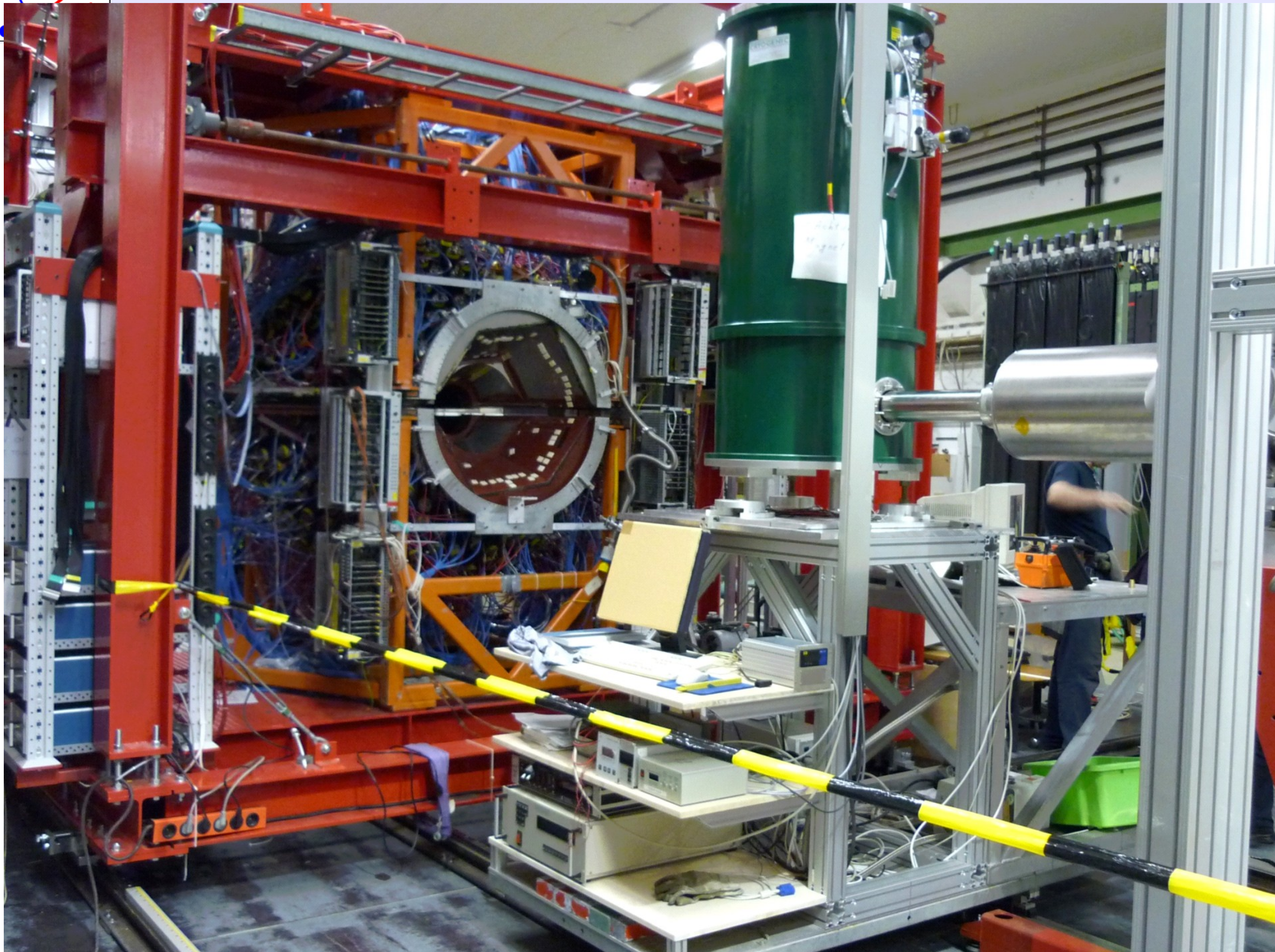
Butanol doped with trityl radical

GDH 2003

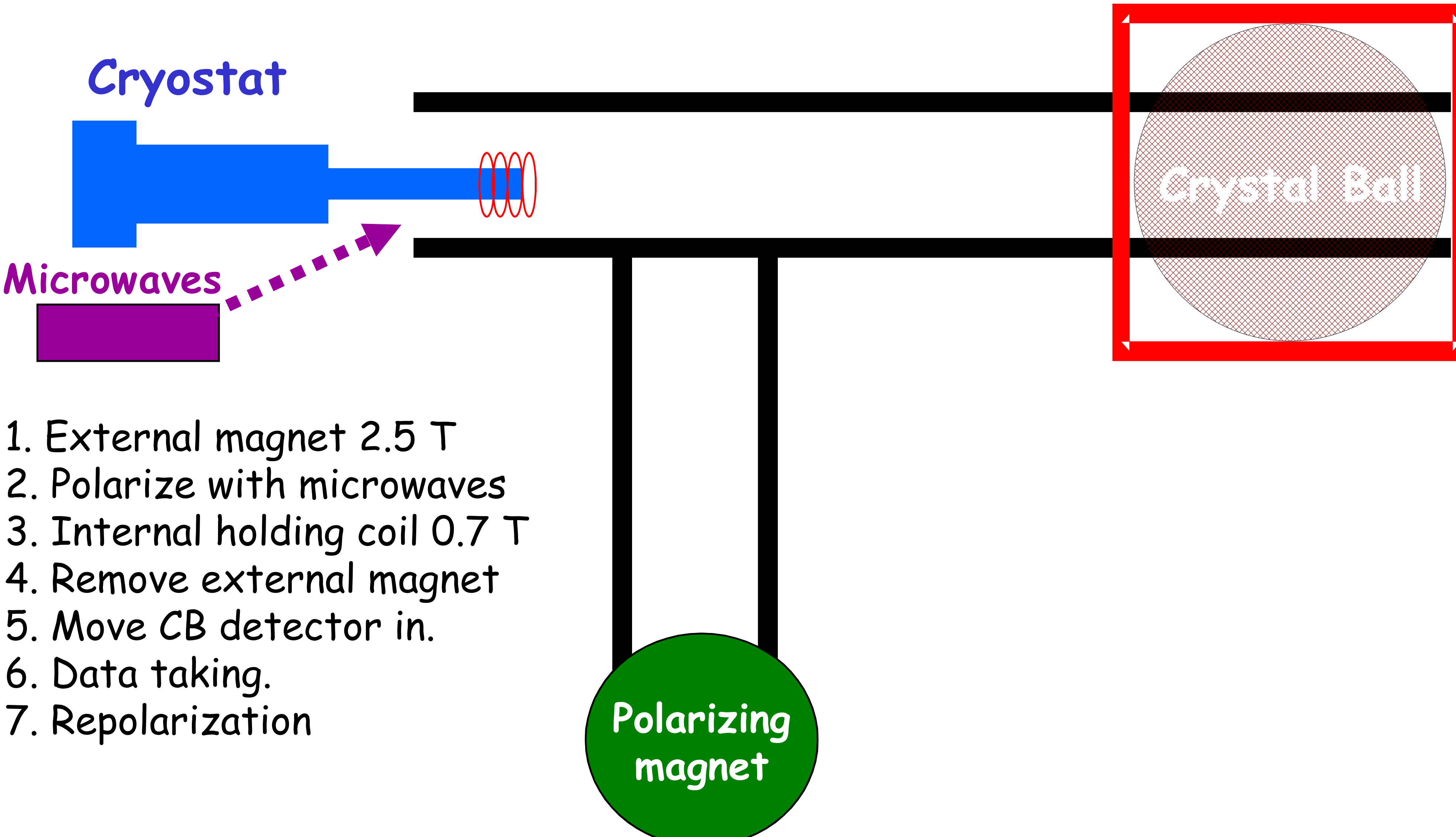
$\overline{P} \approx 65\,\%$

$\overline{P} \approx 29\,\%$

Picture of the Setup

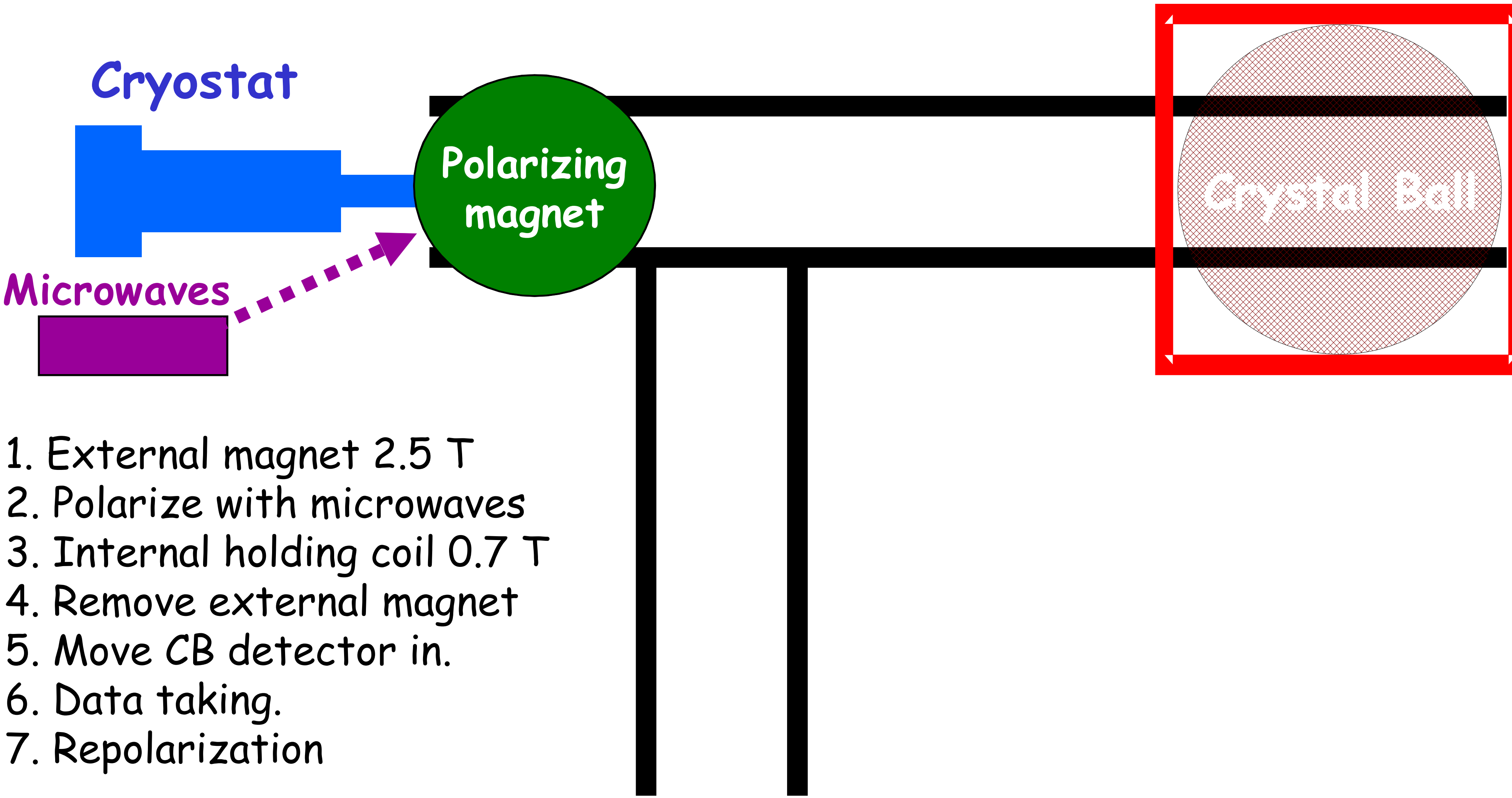


Frozen Spin Target Hump Yard



1. External magnet 2.5 T
2. Polarize with microwaves
3. Internal holding coil 0.7 T
4. Remove external magnet
5. Move CB detector in.
6. Data taking.
7. Repolarization

Frozen Spin Target Hump Yard



1. External magnet 2.5 T
2. Polarize with microwaves
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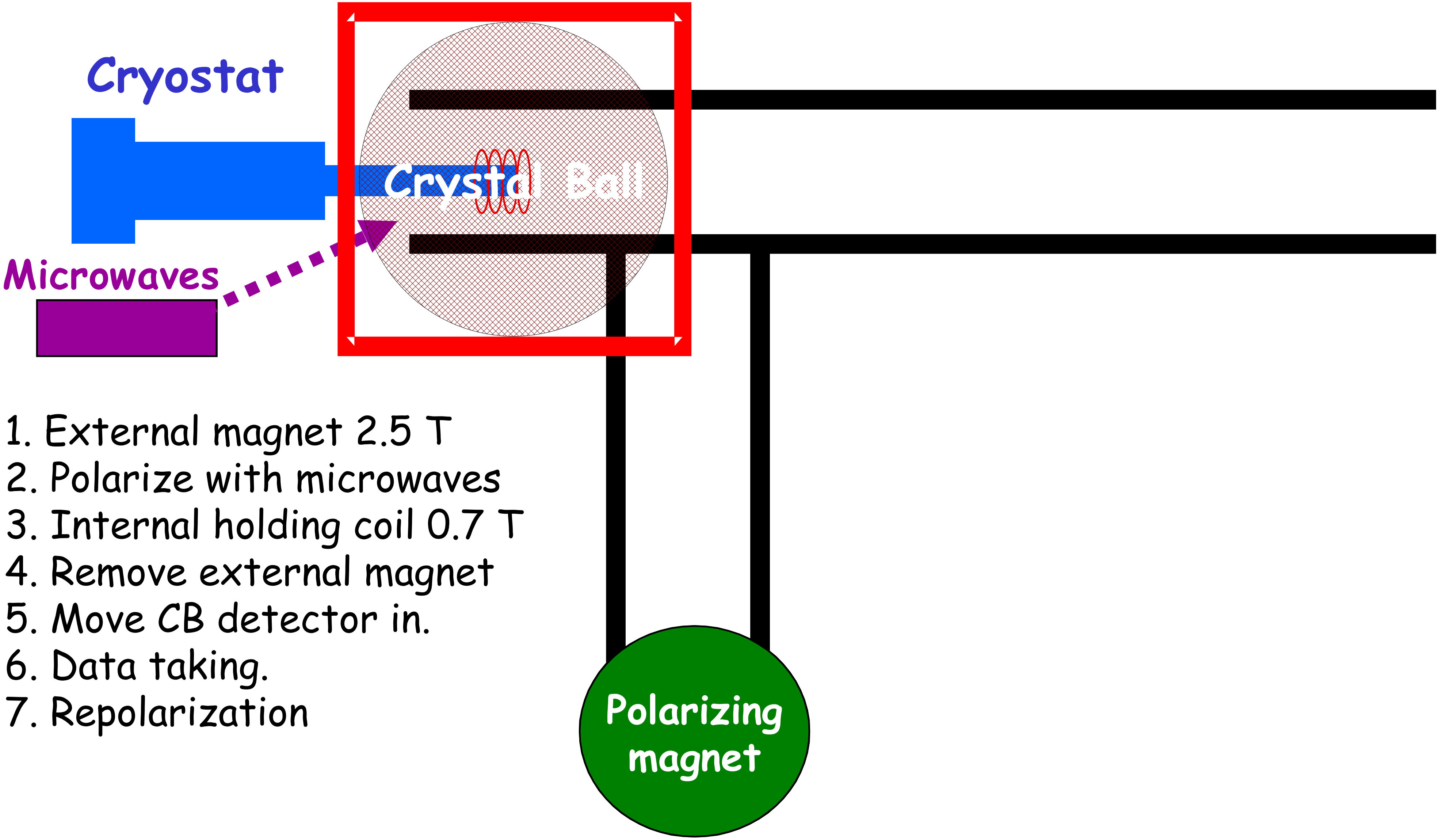
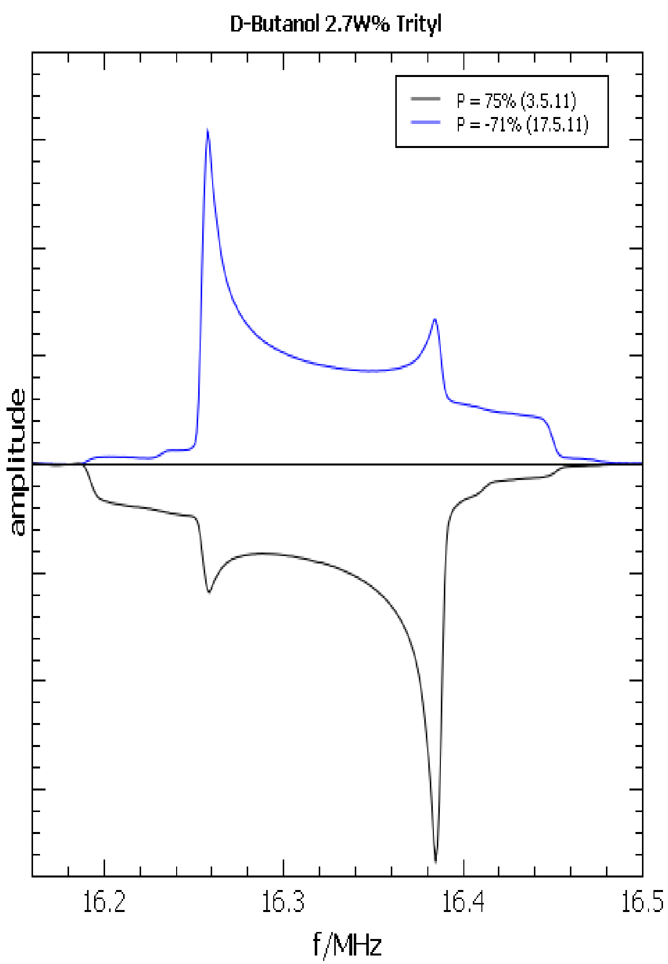
Frozen Spin Target Hump Yard

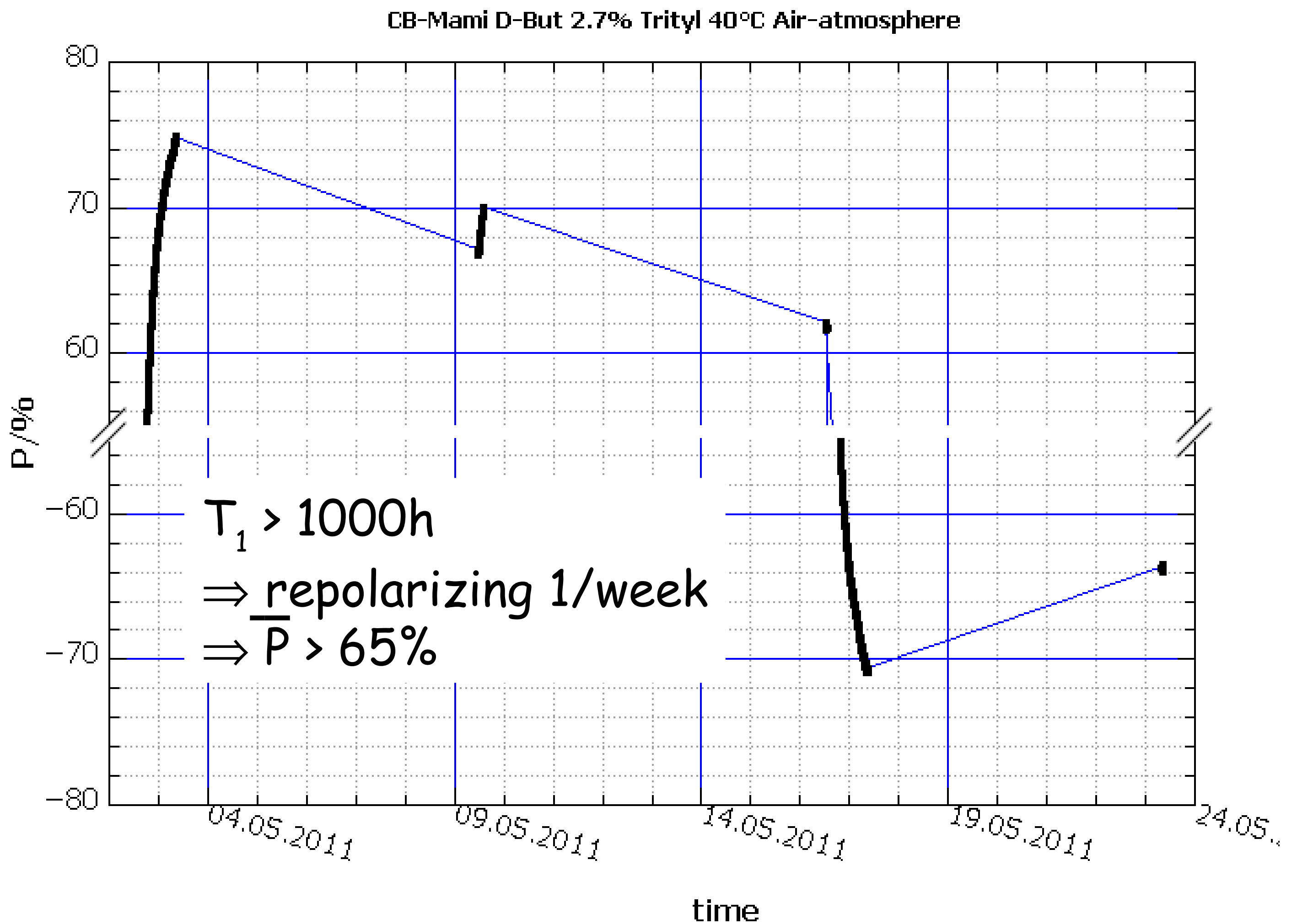


1. External magnet 2.5 T
2. Polarize with microwaves
3. Internal holding coil 0.7 T
4. Remove external magnet
5. Move CB detector in.
6. Data taking.
7. Repolarization

CB-MAMI May 2011

Transversely polarized Deuteron target





Double Polarized Experiments

Excitation Spectrum

1.- Longitudinal PT: a) Helicity dependence E of meson photoproduction
b) Measurement of the G in single pion production

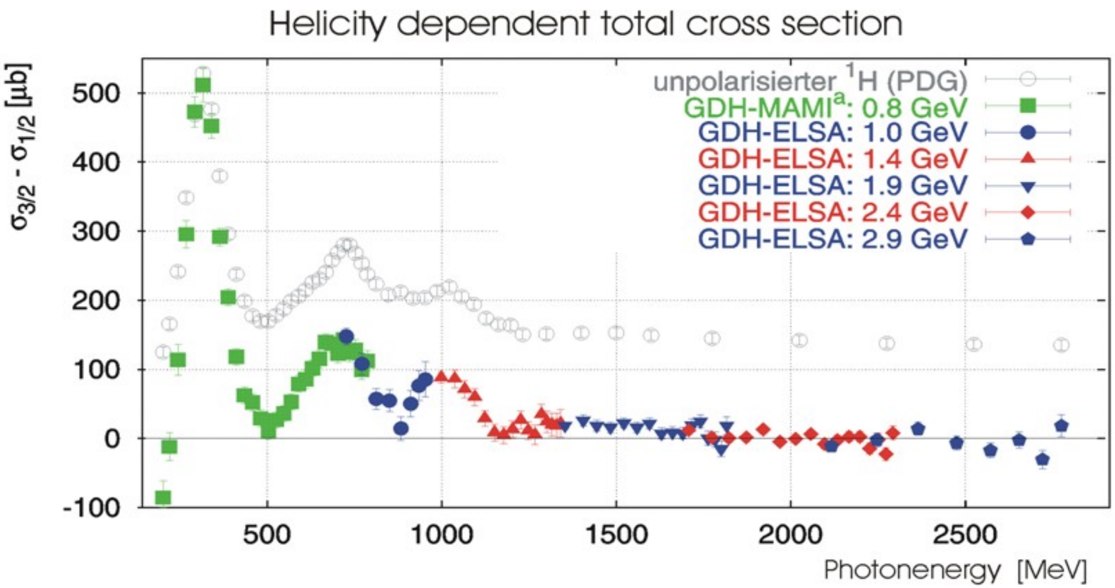
2.- Transverse PT: a) Transverse asymmetries T and F in η-photo-production in the $S_{11}(1535)$ region
b) Spin observables in $\pi\eta$ photoproduction in the $D_{33}(1700)$ region

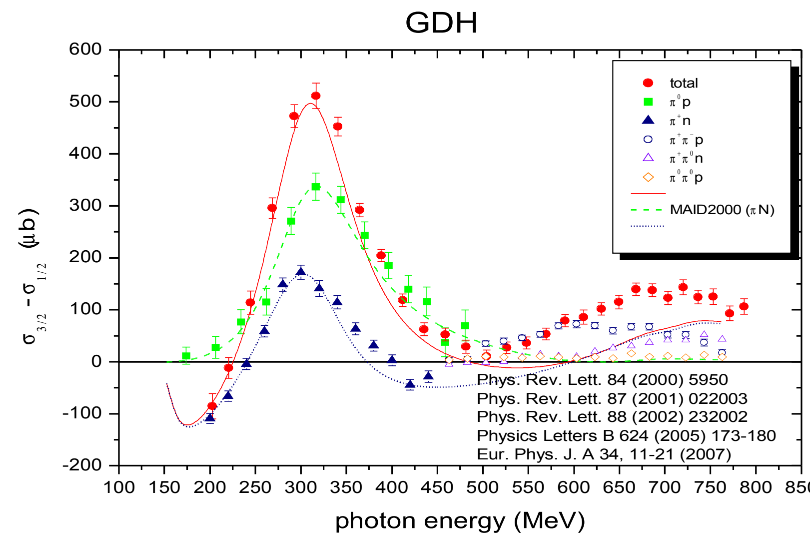
Fundamental Properties

1.- Long. and trans. PT: Spin Polarizibilities

2.- Transverse PT: Transverse asymmetries T and F in π-photo-Production in the threshold region $\Rightarrow m_u - m_d$

A2-06-07/09: Helicity Dependence E of Meson Photoproduction on the Proton (650h + 800h)



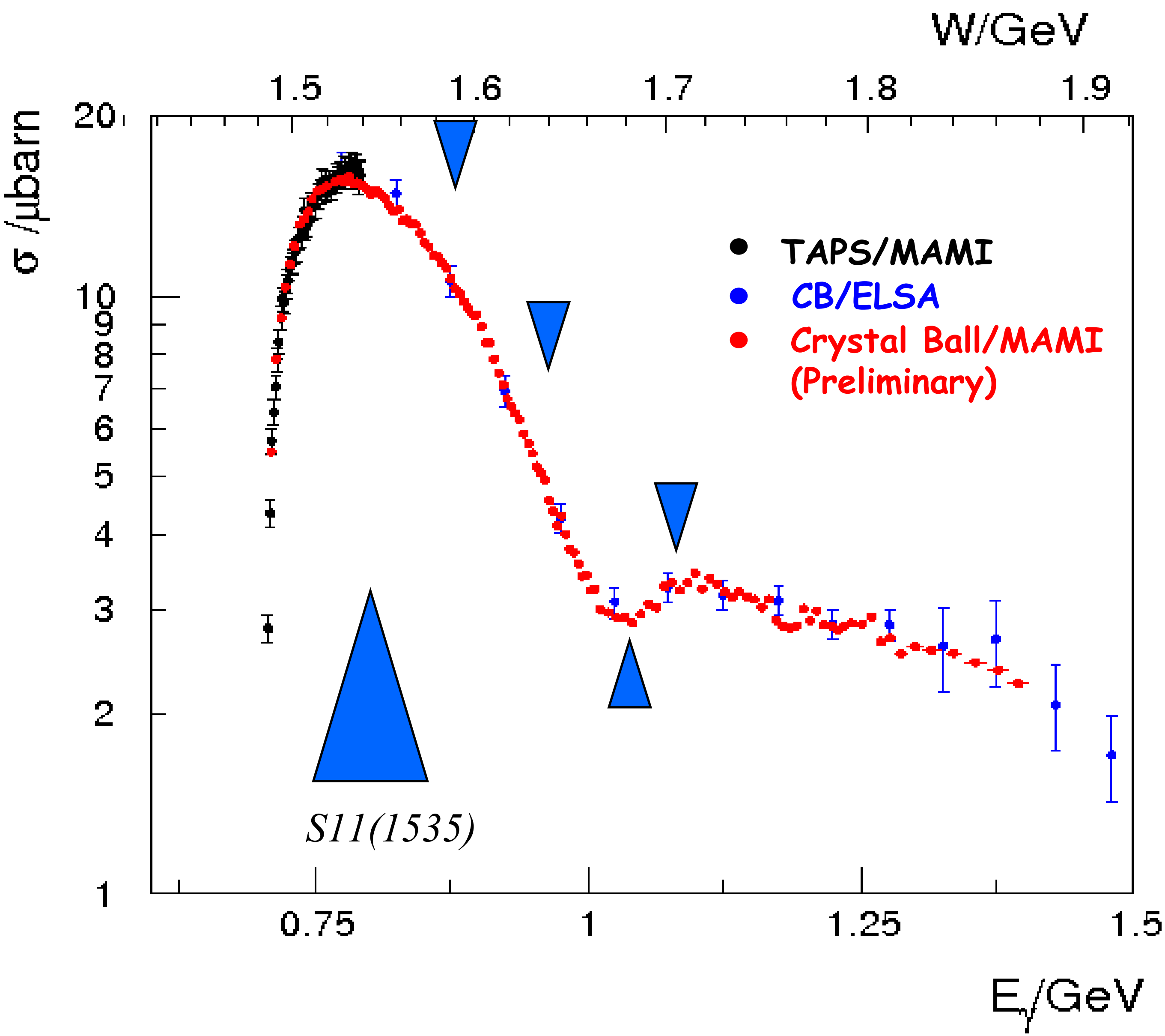


Published data: GDH-Experiment at ELSA and MAMI (DAPHNE).
Preliminary results: 'Crystal Barrel ' and 'CLAS' for E > 500 MeV.
'LEGS experiment at BNL Brookhaven' in the $P_{33}(1232)$ region.

Our proposals: Precise measurement of helicity asymmetry in meson photopro. .
- π^0 production: strongly sensitive to $D_{13}(1520)$, $F_{15}(1680)$.
- η production: investigation of $P_{11}(1710)$, $S_{11}(1650)$, and $F_{15}(1680)$.

G-Asymmetry: Determination of M1- partial wave
(sensitive to Roper-resonance $P_{11}(1440)$).

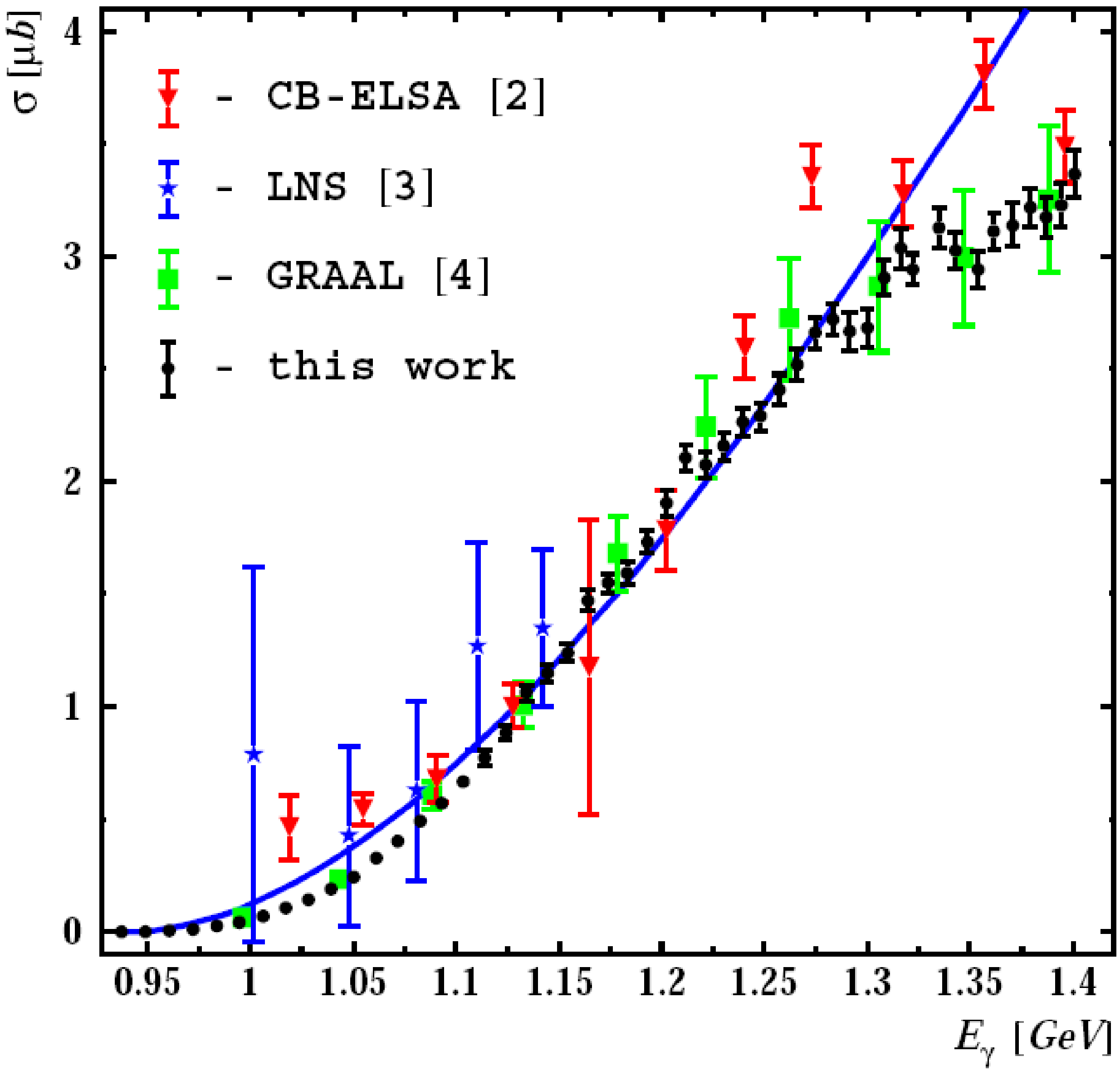
A2-08/09: Transverse asymmetries T and F in η-photoproduction in the S_{11}(1535) region (600 h)



GRAAL/ESRF
Beam asym. data Σ
CLAS/Jlab PT data
CBarrel/ELSA PT data

Narrow structure (Γ<30MeV) in N-Data

A2-09/09: Spin observables in πη photo-production in the D_{33}(1700) region (600 h)



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

A.Fix, Ostrick, Tiator
EPJ. A36, 61-72, (2008)

Data:
V.Kashevarov et al.
EPJ. A 72,141,(2009)

Spin Polarizabilities

Spin Vector polarizabilities describe spin response to an incident photon

Four vector pol. (γ_{E1E1} γ_{M1M1} γ_{E1M2} γ_{M1E2}) appear at 3rd order in eff. Hamiltonian

$$H_{eff}^{(3),spin} = -\frac{1}{2}4\pi\left(\gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}\vec{\sigma}\cdot\vec{B}\times\dot{\vec{B}} - 2\gamma_{M1E2}E_{ij}\sigma_j H_j + 2\gamma_{E1M2}H_{ij}\sigma_j E_j\right)$$

Only two linear combinations of vector polarizabilities measured:

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2} = -1.01 \pm 0.08 \pm 0.10 \times 10^{-4} fm^4$$

$$\gamma_\pi = -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2} = 8.0 \pm 1.8 \times 10^{-4} fm^4$$

The Forward S.P. **γ_0** was determined in GDH-Experiment at ELSA and MAMI (DAPHNE) **:**

$$\gamma_0 = \frac{-1}{4\pi^2}\int_0^\infty \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega^3} d\omega$$

The Backward S.P. **γ_π** was determined from dispersive analysis of backward angle Compton scattering. [B. Pasquini *et al*., Proton Spin Polarizabilities from Polarized Compton Scattering (2007).]

Proton Spin Polarizabilities

Linearly polarized photons, parallel and perpendicular to the scattering plane, unpolarized target

$$\Sigma_3 = \frac{\sigma^{||} - \sigma^{\perp}}{\sigma^{||} + \sigma^{\perp}}$$

Circularly polarized photons (left-handed (L) and right-handed (R)), longitudinally polarized target

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

Circularly polarized photons (left-handed (L) and right-handed (R)), transversely polarized target

$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}}$$

Summary

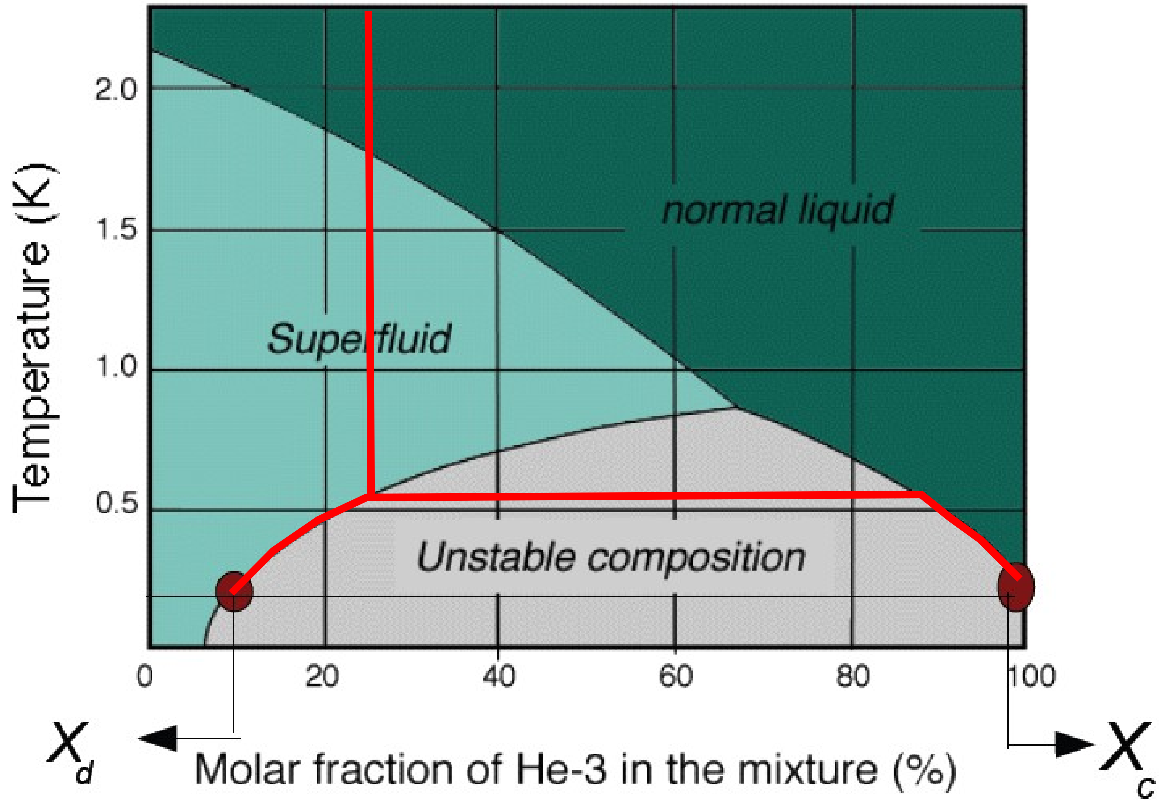
- The new frozen spin target at MAMI is running
- Data taking with CBall-TABS-detector system since February 2010
- Spin observables with focus to $P_{11}(1440)$, $S_{11}(1535)$, and $D_{33}(1700)$ resonance regions. Complete Experiment.
- First Measurement of 4 Vector Spin Polarizabilities and T in π-threshold region planned.

- Production of an internal polarizing coil avoids hump yard. FoM better.
- R&D for polarized active szintillator target for threshold production.

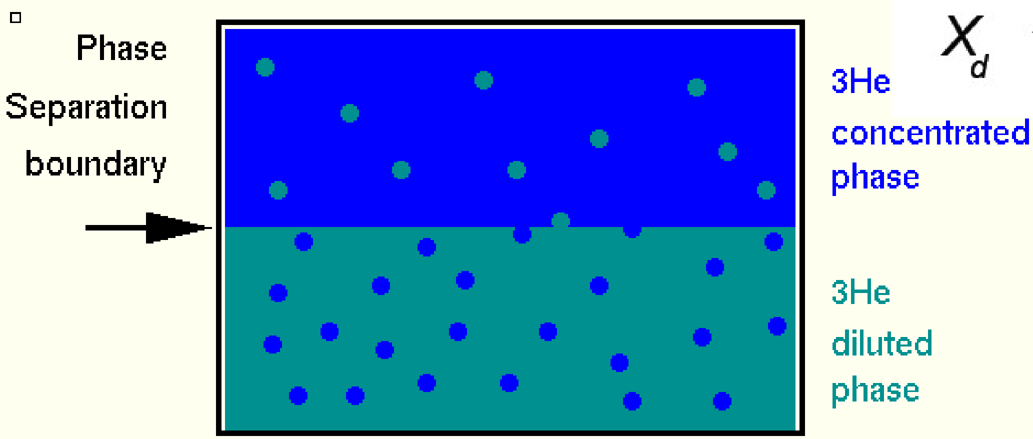
^{3}He-^{4}He-Dilution Cooling

^{3}Helium: Spin $\frac{1}{2}$, Fermion
^{4}Helium: Spin 0, Boson

Cooling a 25%- gas-mixture
from 300K to 0.6K



Separation of both phases



Mixing Chamber

Further cooling using „dilution effect“

^{3}Helium absorbs energy when it dissolved into diluted phase

$$Q = n \cdot [H_d(T) - H_c(T)] \approx 82nT^2$$

Heat Q absorbed by n moles 3Helium

Distillation in the „Still" at 0.7K

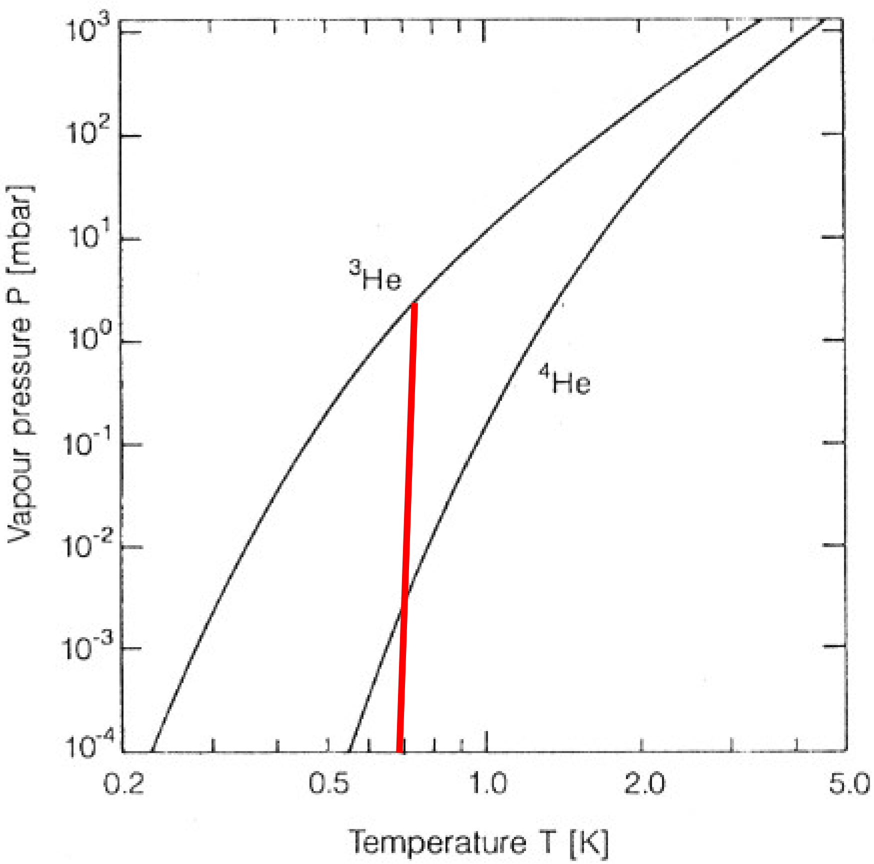
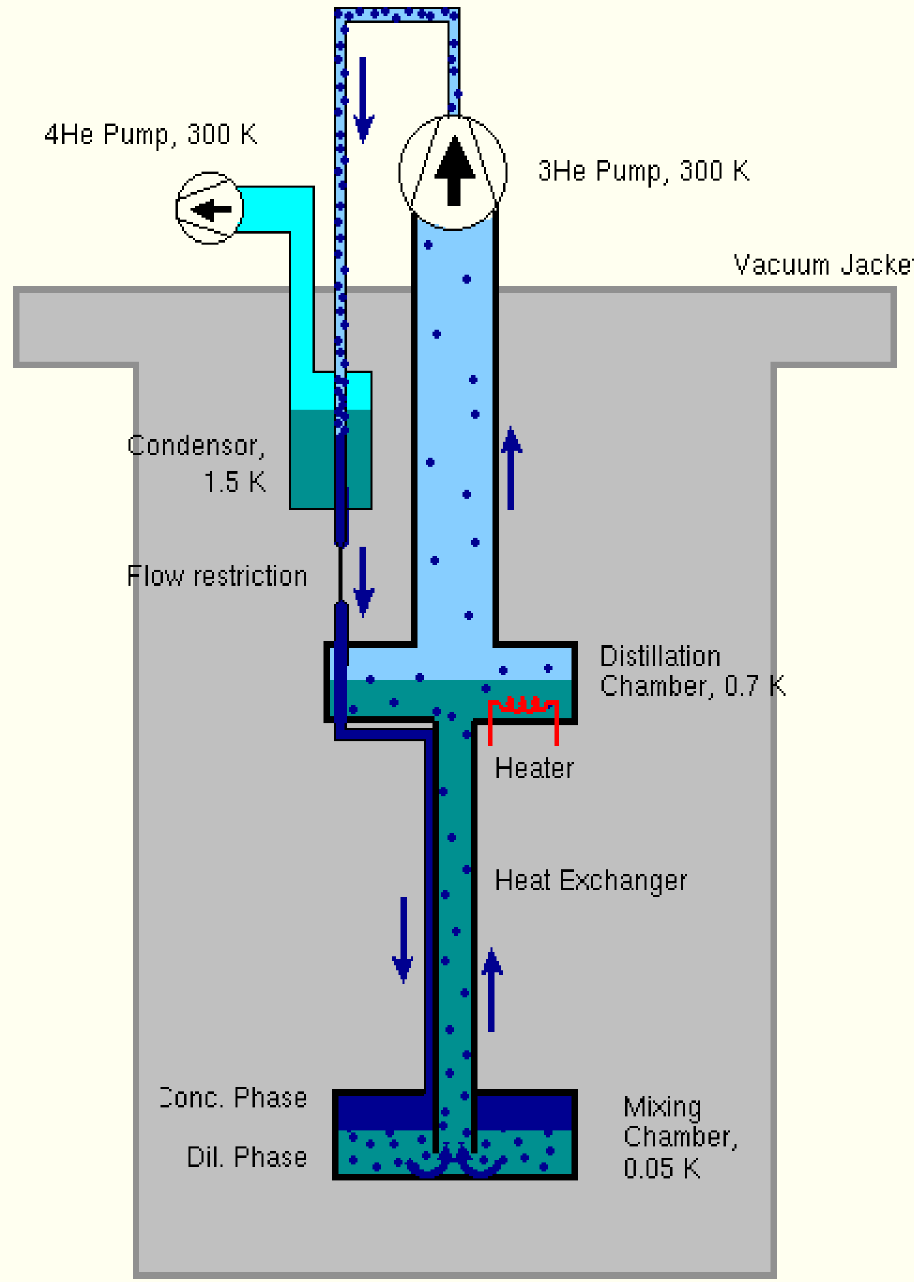


Fig.2.6. Vapour pressures of liquid ^{3}He and liquid ^{4}He



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RUB

D-Materials

Material	Doping method	abs. max. Polarization	B-Field	Experiment / Laboratory
^{6}LiD	Irradiation	> 50 %	2.5 T (<0.1 K)	COMPASS
D-Butanol	Irradiation	> 55 %	2.5 T (<0.1 K)	Bochum
		> 70 %	5.0 T (<0.1 K)	Bochum
ND_3	Irradiation	> 50 %	3.5 T (0.3 K)	Bonn
D-Butanol	Trityl (chem. dop.)	> 80 %	2.5 T (<0.1 K)	GDH Mainz
D-Propandiol	Trityl (chem. dop.)	> 80 %	2.5 T (<0.1 K)	Bochum
D-Styrene	Trityl (chem. dop.)	> 30 %	2.5 T (0.4 K)	Bochum
		> 60 %	5.0 T (0.4 K)	Bochum

Measurement time

Calculations are made for same target volume

Deuteron materials					
Material	P	ρ[g/cm³]	f	F[10^{-2} g/cm³]	t/t_{HD}
D-Butanol	80%	1.07	0.24	3.88	0.42
ND_3	50%	1.02	0.30	1.78	0.91
^{6}LiD	50%	0.82	0.50	5.13	0.31
HD	50%	0.15	0.67	1.61	1.00
D-Polystyrene	60%	1.05	0.14	0.77	2.1

Radiation length

$$\frac{1}{X_0} = 4 \alpha r_e^2 \frac{N_A}{A} \left(Z(Z+1) \ln \frac{287}{\sqrt{Z}} \right)$$

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1) \ln \frac{287}{\sqrt{Z}}} g \cdot cm^{-2}$$

α fine structure constant

r_e classic radius of electron

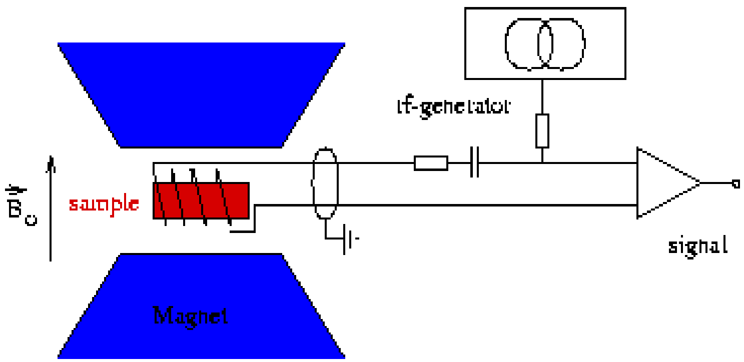
N_A Avogadro -constant

A atomic mass

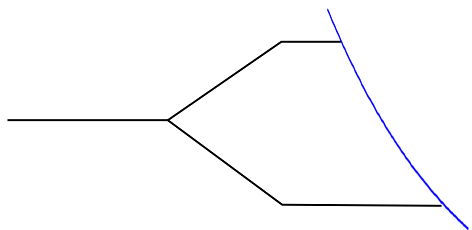
Z atomic number

Material	ρ [g/cm^3]	X_0 [g/cm^2]
H-Butanol	0.94	45.6
NH_3	0.85	41.1
D-Butanol	1.07	46.2
LiD	0.82	78.9
HD	0.15	94.9

Polarization detection by NMR



Applying a static magn. field B_0 to a spin ensemble leads to a degeneration into 2s+1 sublevels, the shift of the sublevels is given by $E_{magn}(m)=m\,\hbar\,\omega_L$ (ω_L :Larmor-frequency)

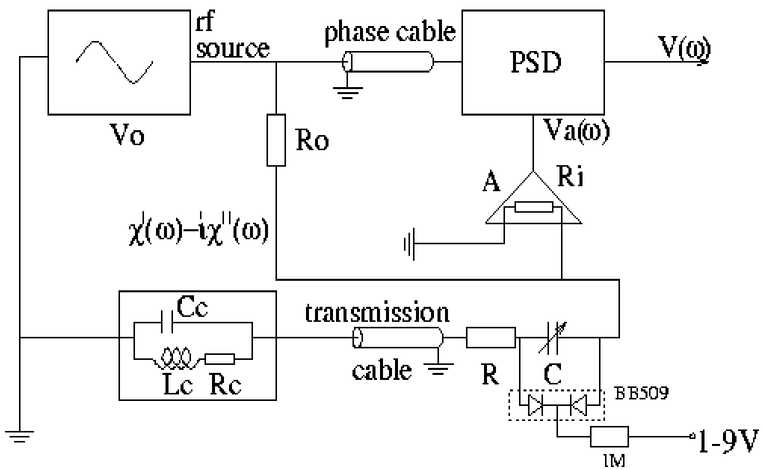


$$\frac{N_2}{N_1}=e^{\frac{\hbar\omega_L}{k_B T}}$$

Boltzmann-distribution among the m-sublevels: $N_m \propto \exp\left[-E_{magn}(m)/k_B T\right]$

$$P:=\frac{\langle S_Z\rangle}{S}=\frac{\sum_{m=-s}^{+s} m N_m}{S\sum_{m=-s}^{+s} N_m} \qquad \Rightarrow \langle S_Z\rangle=\frac{\sum_{m=-s}^{s}\hbar\, m\exp\left[-E_{magn}(m)/k_B T\right]}{\sum_{m=-s}^{s}\exp\left[-E_{magn}(m)/k_B T\right]}$$

CW NMR

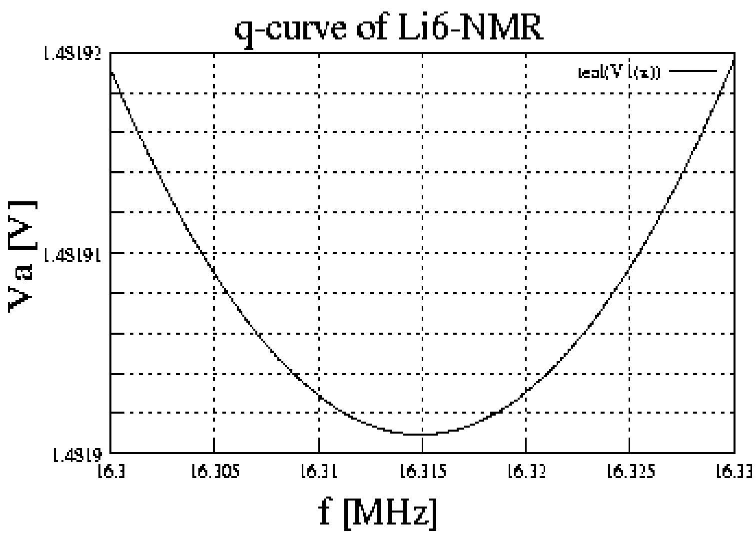


$$P = \frac{2\hbar s}{g^2 \mu_N^2 N \pi} \int_0^\infty \chi''(\omega) \frac{\omega_0}{\omega} d\omega \equiv \frac{2\hbar s}{g^2 \mu_N^2 N \pi} A$$

A is the area under the signal

$$P = k \int_{\Delta\omega} S(\omega) d\omega$$

k includes the properties of the material and of the Q-meter



Series Q-meter:

$$V_a(\omega, \chi) = \frac{GV_0}{R_0} \frac{Z(\omega, \chi)}{1 + x\ Z(\omega, \chi)}$$

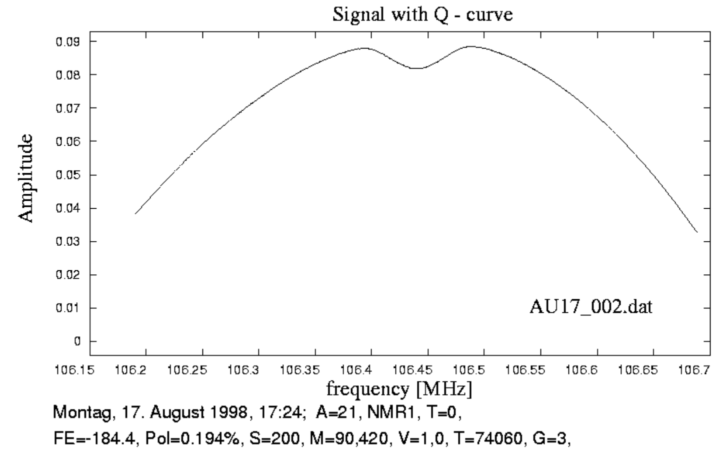
with $x = 1/R_0 + 1/R_i$ as admittance,
G as the gain of the amplifiers
and $Z(\omega, \chi)$ as circuit impedance

TE method

- Acquire NMR signals at thermal equilibrium
(T and B are known)

$$P_s = \frac{2s+1}{2s} \cdot \coth\left(\frac{2s+1}{2s}\alpha\right) - \frac{1}{2s}\coth\left(\frac{1}{2s}\alpha\right)$$

$$\alpha = \frac{g\,\mu_N\,s\,B}{k_B\,T}$$

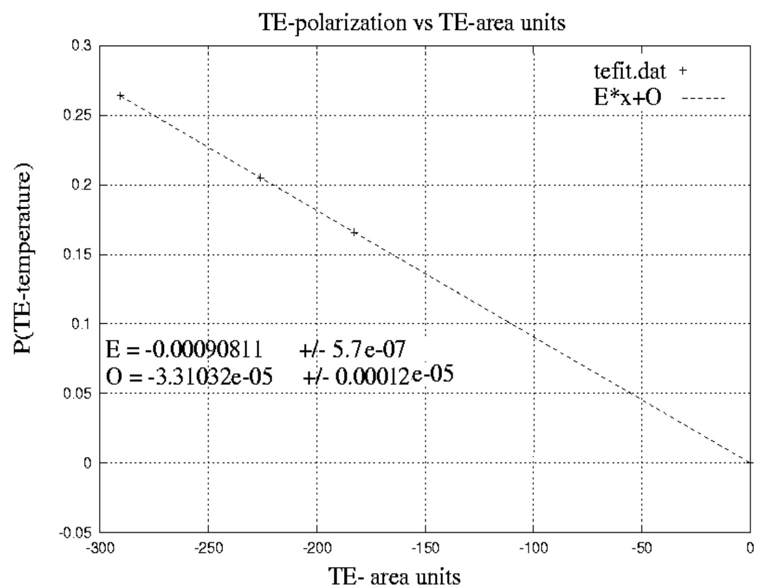


- Area under the line shape is proportional to P

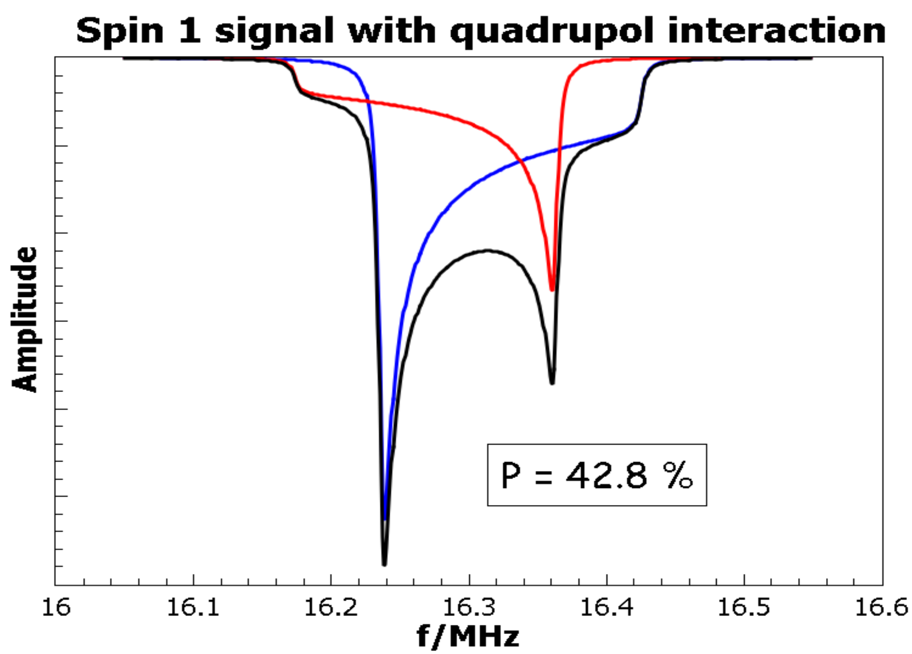
$$K = \frac{P_{TE}}{AU_{TE}}$$

- Dynamical polarization

$$P_{dyn} = K \cdot AU_{dyn}$$



Asymmetry-method (line shape)



- -Quadrupol moment interacts with electrical field gradient (if consisting)
- 2 transitions (-1 – 0) and (0 – 1)
- P = f(ratio of the tr. rates)
- r = 0.7 -> P = -23.3%

$$r = \frac{H1}{H2} \qquad P = \frac{r^2 - 1}{r^2 + r + 1}$$

- Quadrupol line shape function is fitted to the signal and r is extracted PHD Th. Chr. Dulya 1996

$$\chi(\omega) = \frac{N}{\omega_Q}\left(\frac{r^2 - r^{1-3qR}}{r^{1-qR}} F_{plus}(R) + \frac{r^{1+3qR} - 1}{r^{1+qR}} F_{minus}(R)\right)$$