LEPSの物理と標的

Feb / 24 / 2020

RCNP Osaka University / Nagoya University

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Super Photon ring - 8 GeV

Electron storage ring

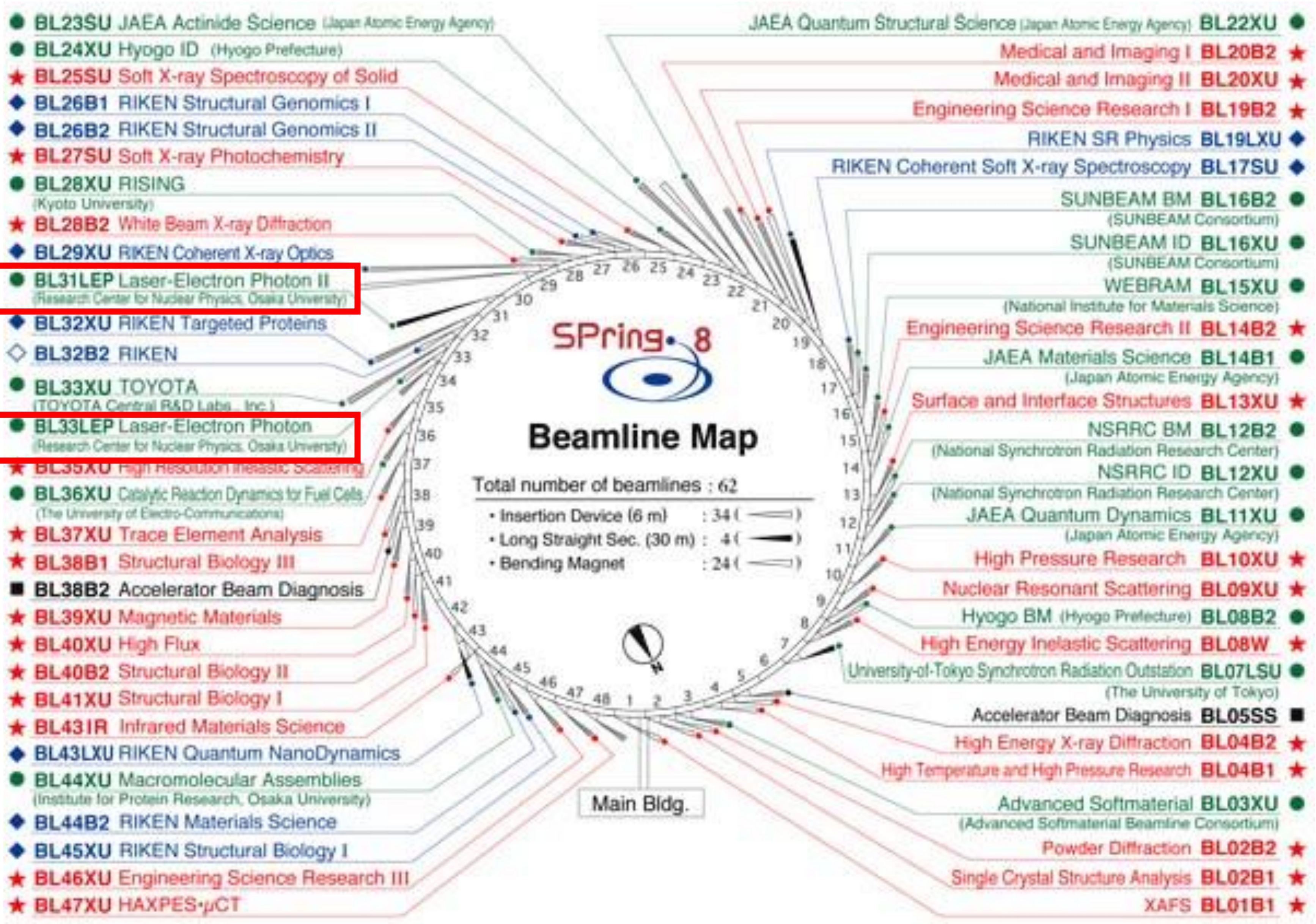
- 8 GeV electron beam
- Diameter ≈457 m
- RF 508 MHz
- 1-bunch spread is
  within $\sigma = 12$ psec.
- Beam Current = 100 mA

120 km distant from Osaka

SPring-8 beamline map

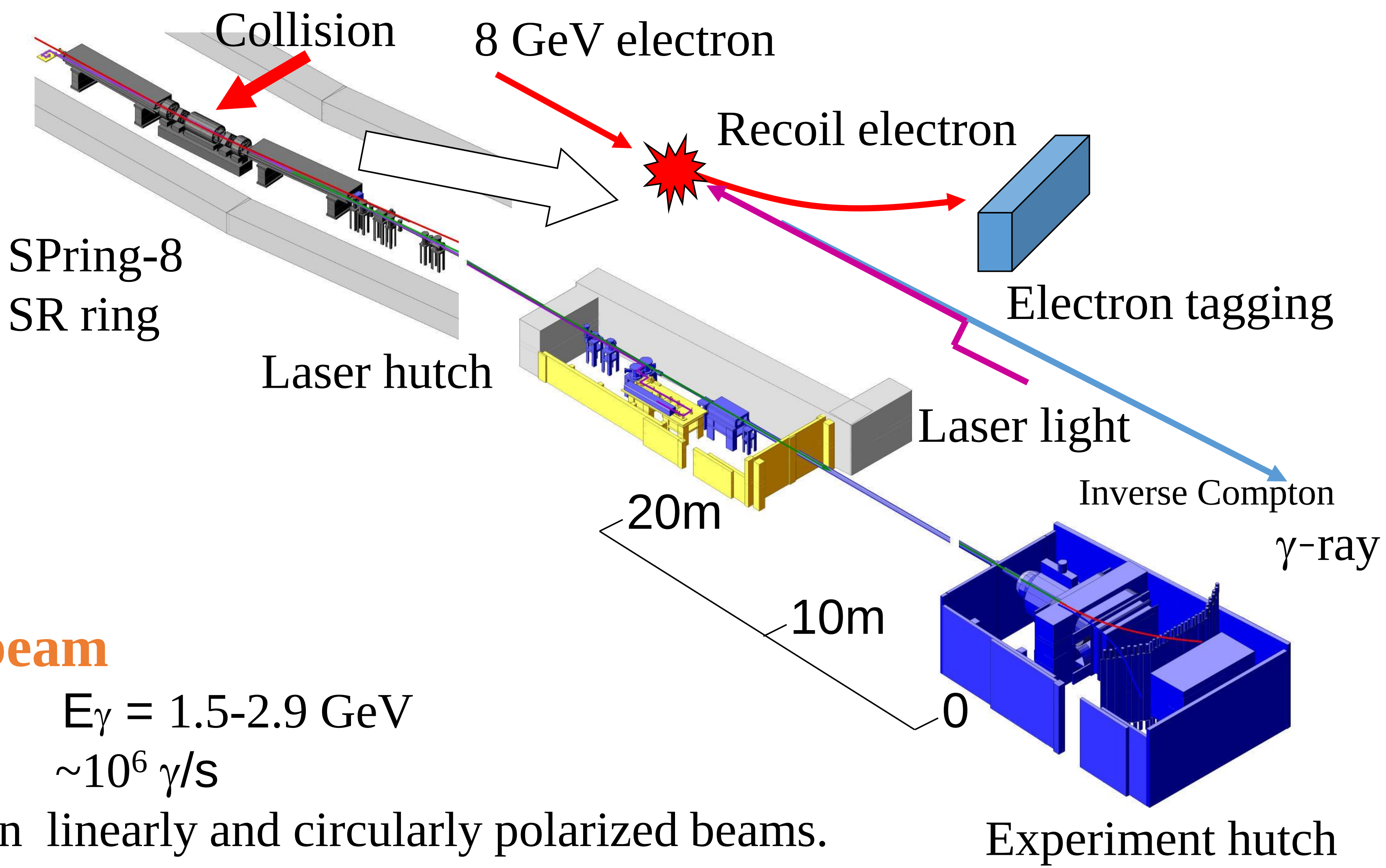
LEPS2

LEPS



LEPS beamline

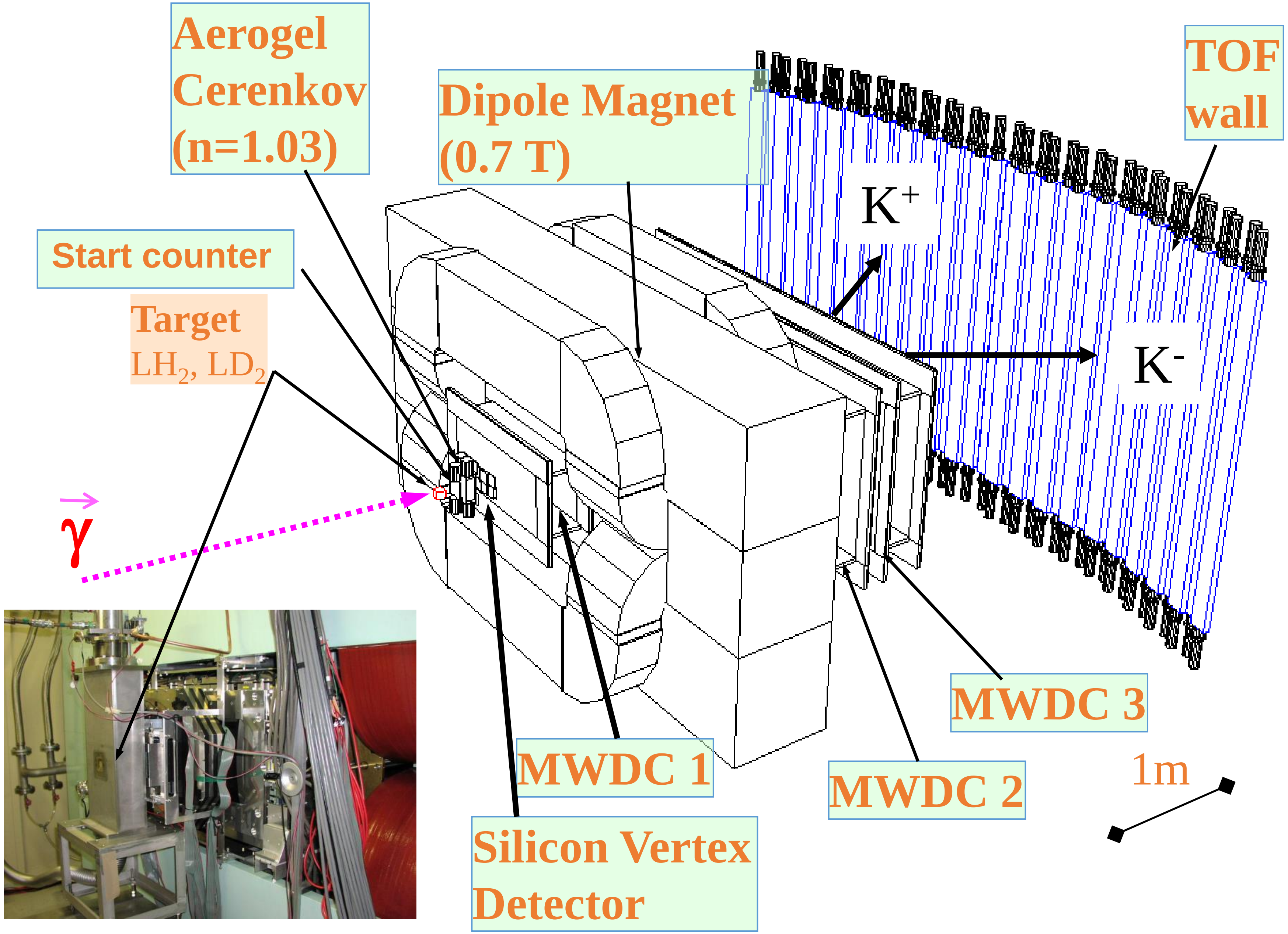
LEPS facility constructed in 2000



Photon beam

Energy E_γ = 1.5-2.9 GeV
Intensity ~10^6 γ/s
Polarization linearly and circularly polarized beams.
P~90% at the maximum photon energy.

LEPS detector (optimized to detect φ decaying to K^+K^-)



One of our physics objectives is to understand how hadrons are produced

I want to obtain unified understanding of various $q\bar{q}$ productions.

(1) γ p -> $\pi^- \Delta^{++}$ reaction — $u\bar{u}$ production in the final state

H. Kohri et al., Phys. Rev. Lett. 120, 202004 (2018)

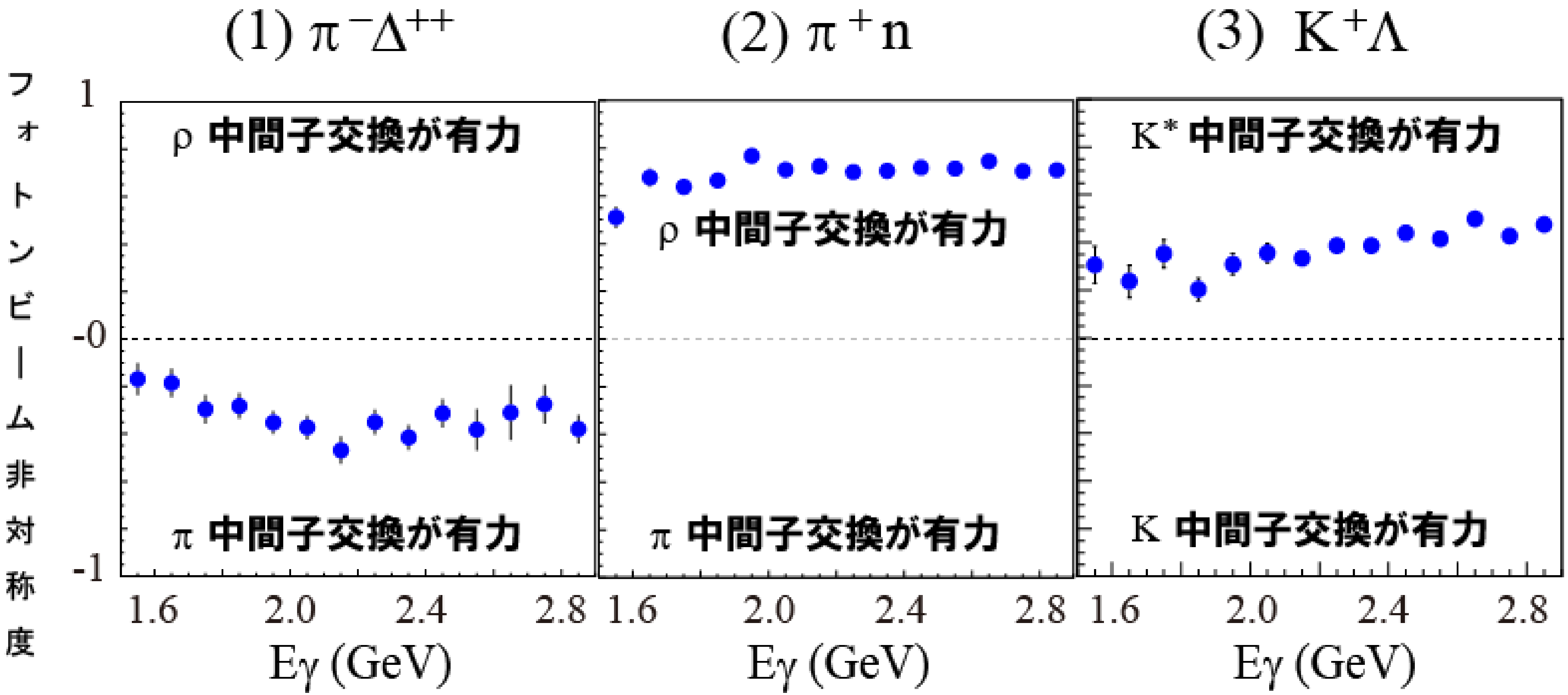
(2) γ p -> π^+ n reaction — $d\bar{d}$ production in the final state

H. Kohri et al., Phys. Rev. C 97, 015205 (2018)

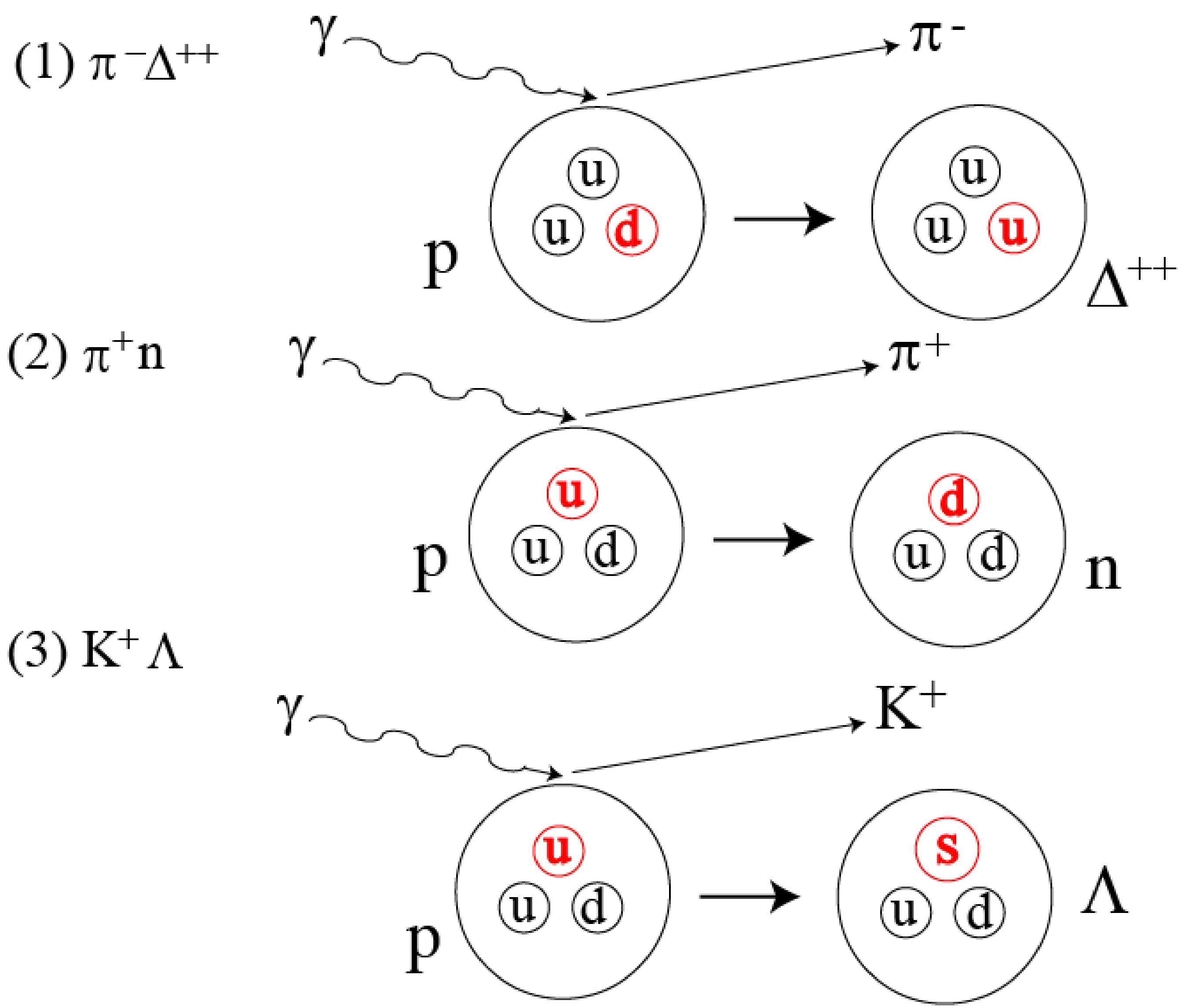
(3) γ p -> $K^+ \Lambda$, $K^+ \Sigma^0$ reactions — $s\bar{s}$ production in the final state

S.H Shiu, H. Kohri et al., Phys. Rev. C 97, 015208 (2018)

Photon beam asymmetry, measured by linearly polarized γ, is sensitive to reaction mechanisms



My personal interpretation



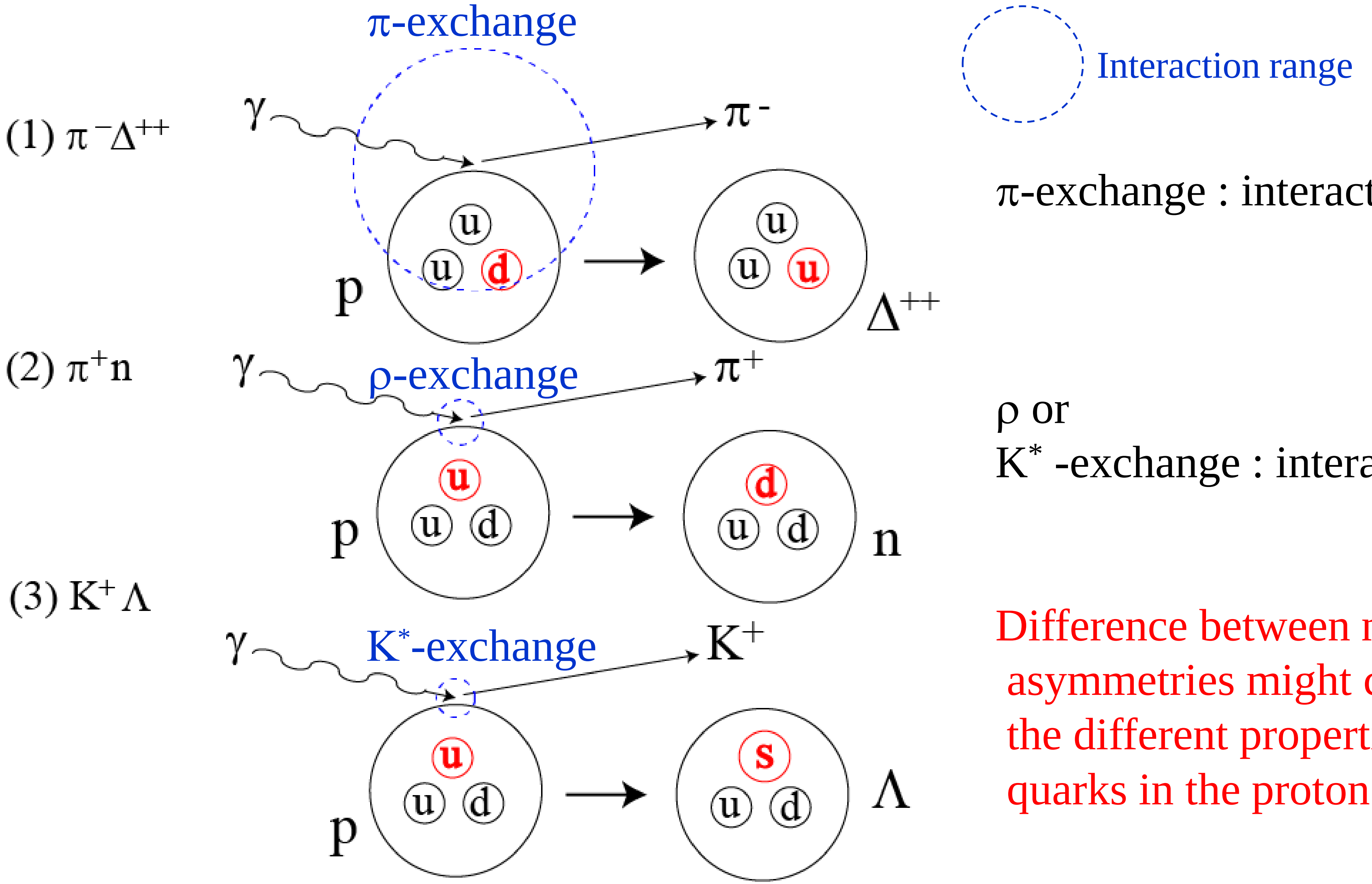
π^-, π^+, and K^+ were detected at forward angles.

(1) $\pi^-\Delta^{++}$ reaction exchanges d quark with u.
π -exchange is dominant.

(2) π^+ n reaction exchanges u quark with d.
ρ-exchange is dominant.

(3) $K^+\Lambda$ reaction exchanges u quark with s.
K^*-exchange is dominant.

My personal interpretation



π-exchange : interaction range is long.

ρ or
K^* -exchange : interaction range is short.

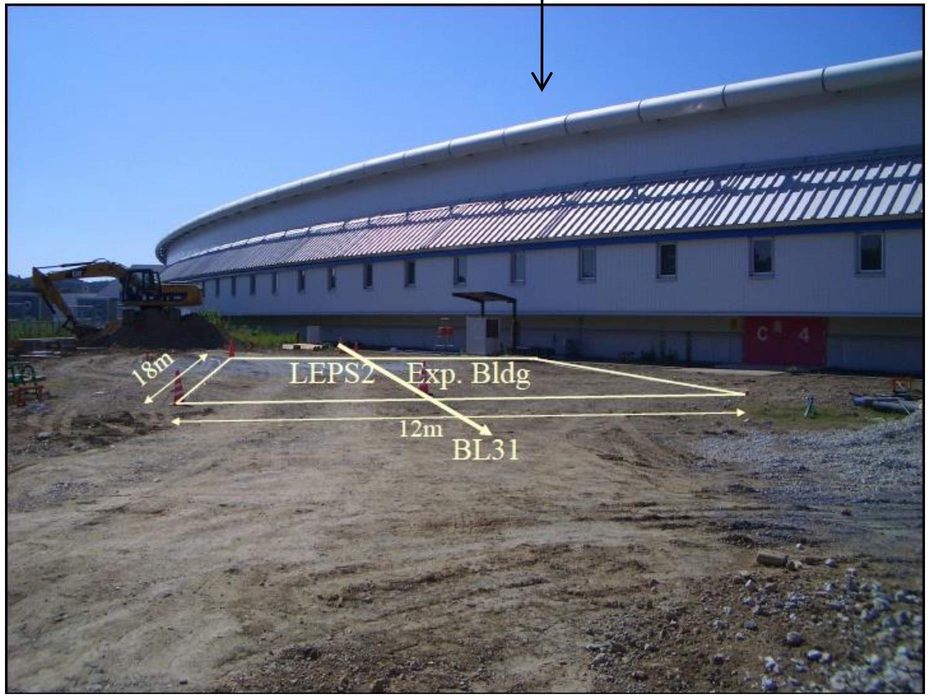
Difference between negative and positive asymmetries might come from the different properties between d and u quarks in the proton.

LEPS2 beamline

LEPS2 experiment hutch was constructed with the special support of RIKEN in 2011

Experiment hall of SPring-8

LEPS2 experiment hutch



2010

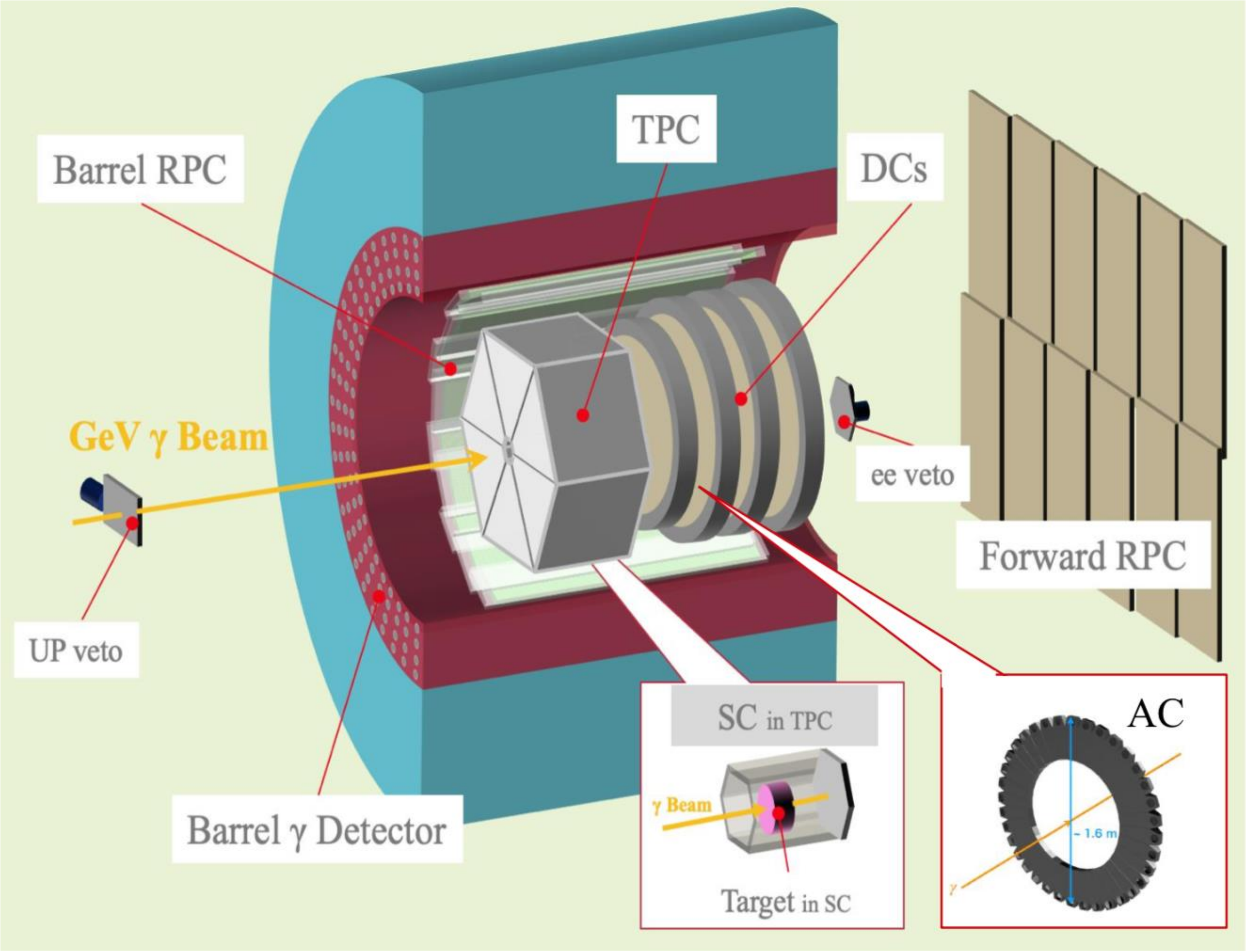
August 2011

Solenoid

BNL-E949 spectrometer was transported to SPring-8

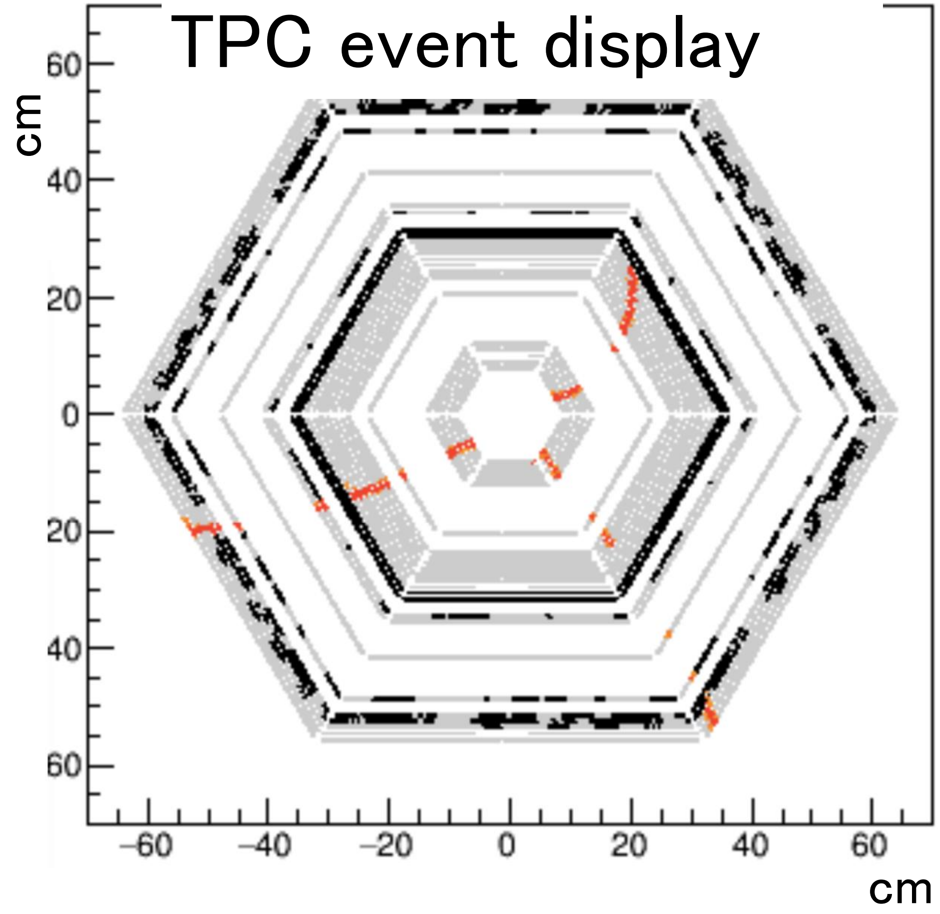
SPring-8 LEPS2 experiment hutch

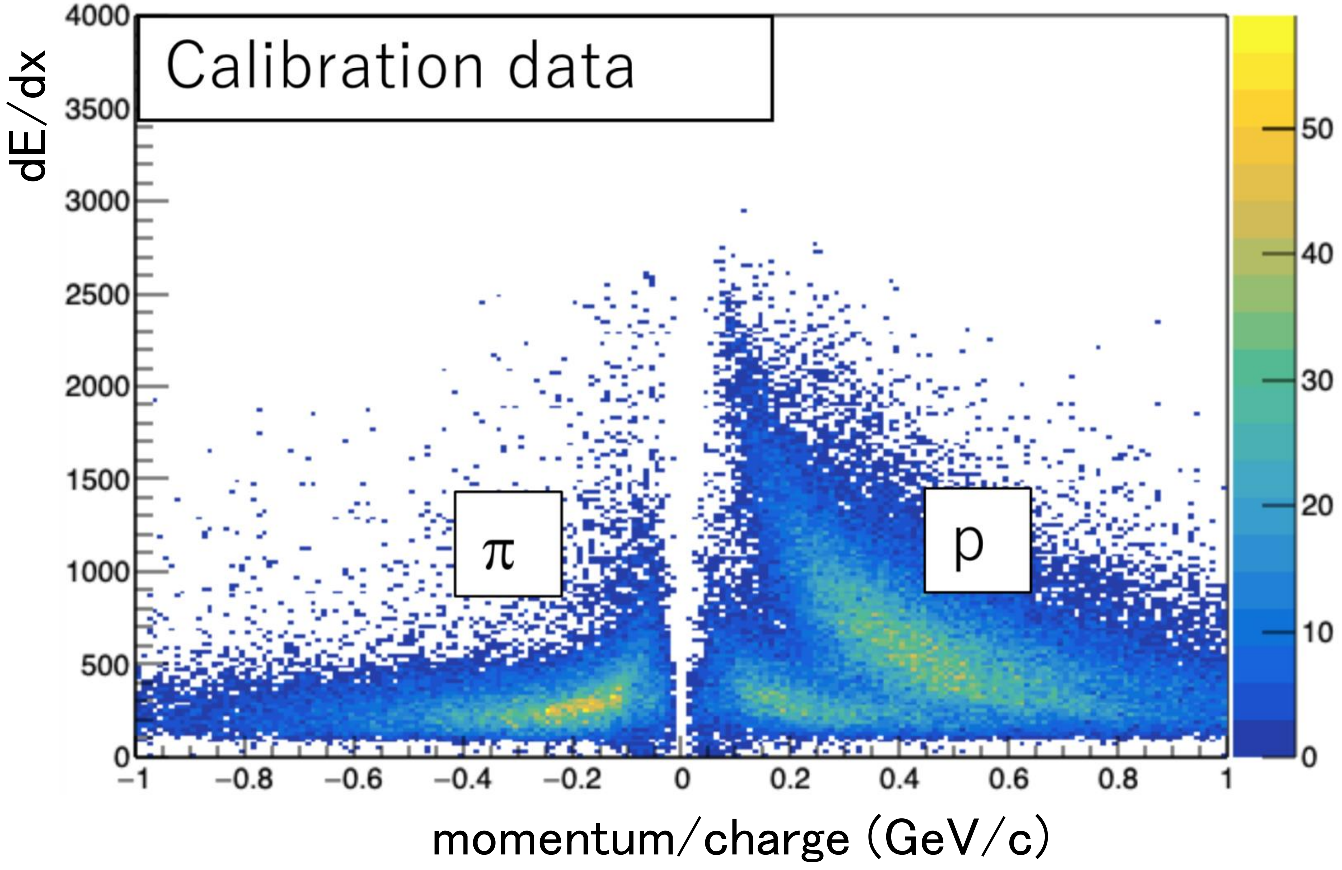
Solenoid spectrometer@SPring-8/LEPS2



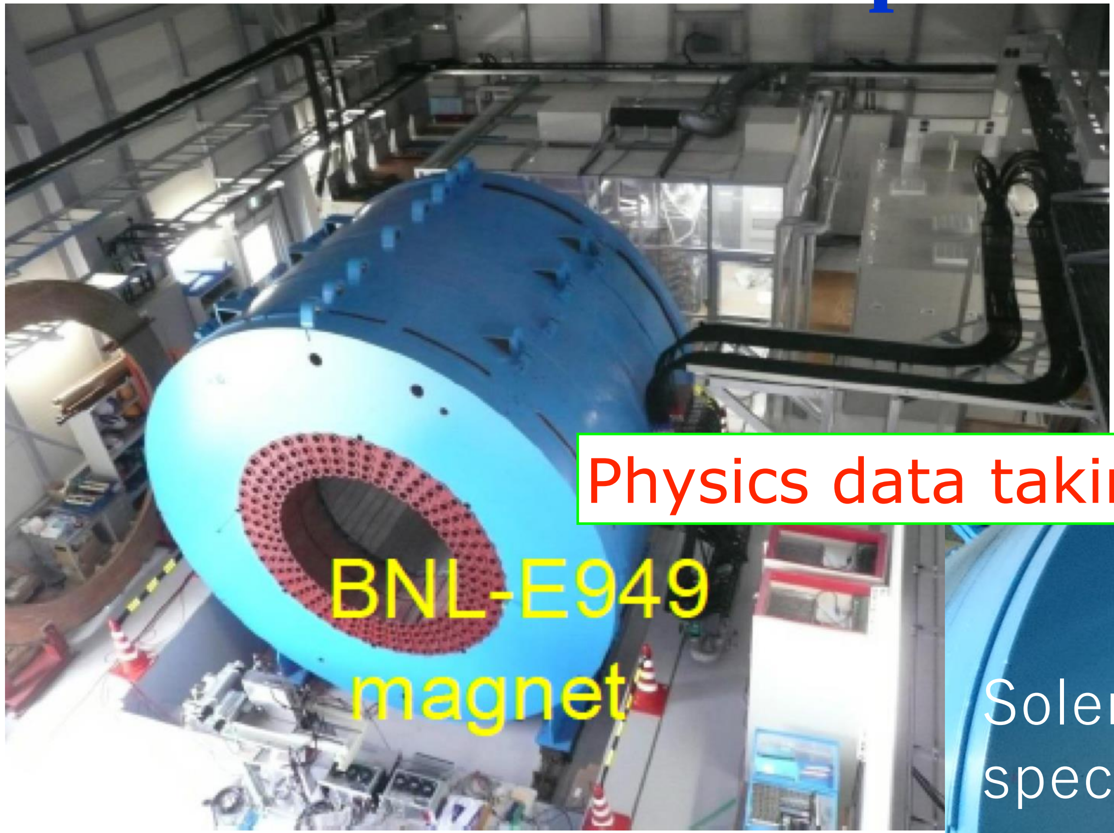
- 0.9 T magnetic field
  momentum resolution 1~7%
- Charged particles (7° – 110°)
  Time Projection Chamber (TPC)
  Drift Chamber (4 DCs)
- γ-ray counters (40° – 110°)
  Lead-plastic EM cal. (6.48 X_0)
- Time-of-flight counters
  Resistive Plate Chamber (RPC)
- Aerogel Cherenkov Counter

Solenoid spectrometer@SPring-8/LEPS2

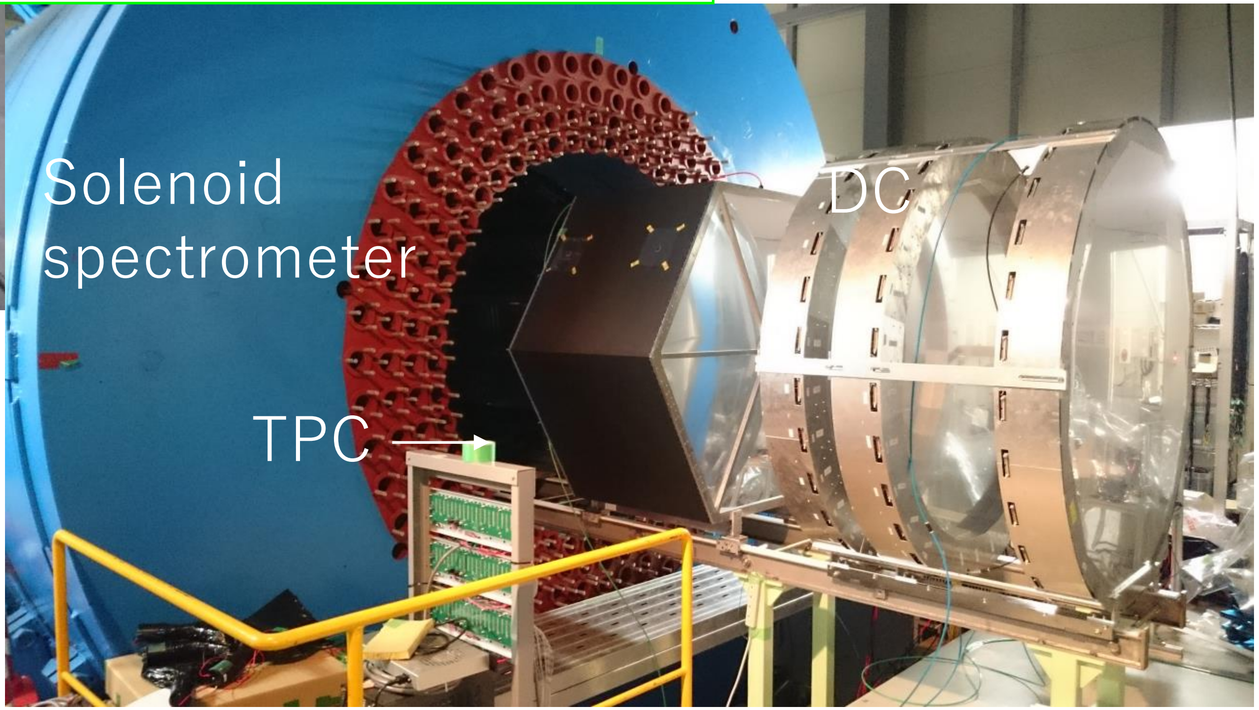




LEPS2 solenoid spectrometer @ SPring-8



Physics data taking will start soon

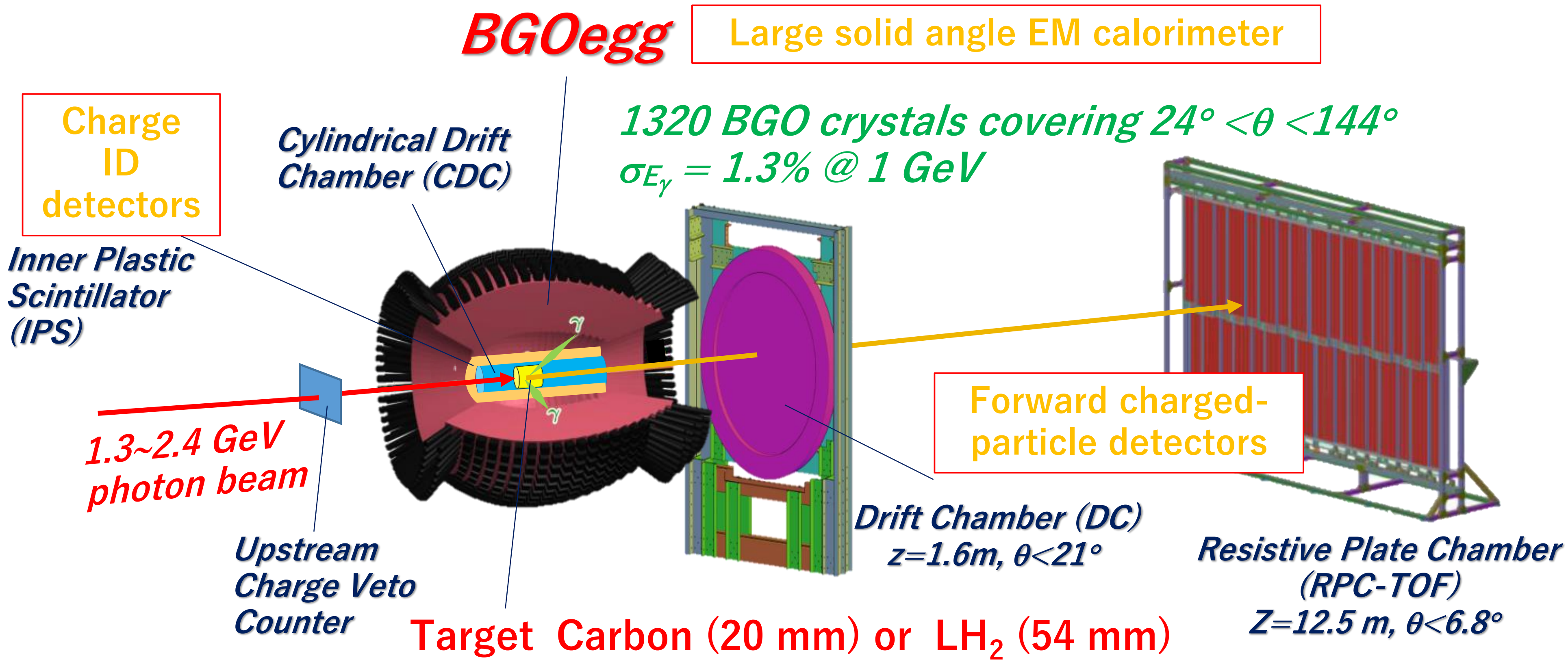


BGOegg

BGOegg experiment

Carrying out research programs for **photoproduction of neutral hadrons decaying γ's** using **a large solid angle electro-magnetic calorimeter** with **the world-best energy resolution**.

- Investigating **the origin of hadron mass** via **η′ meson in nuclei**.
- Studying **hadron structures** via **baryon resonance search**.



η′ mass in nuclei

The η′-meson mass arises from **$U_A(1)$ quantum anomaly** under **the spontaneous breaking of chiral symmetry (SBχS)**.

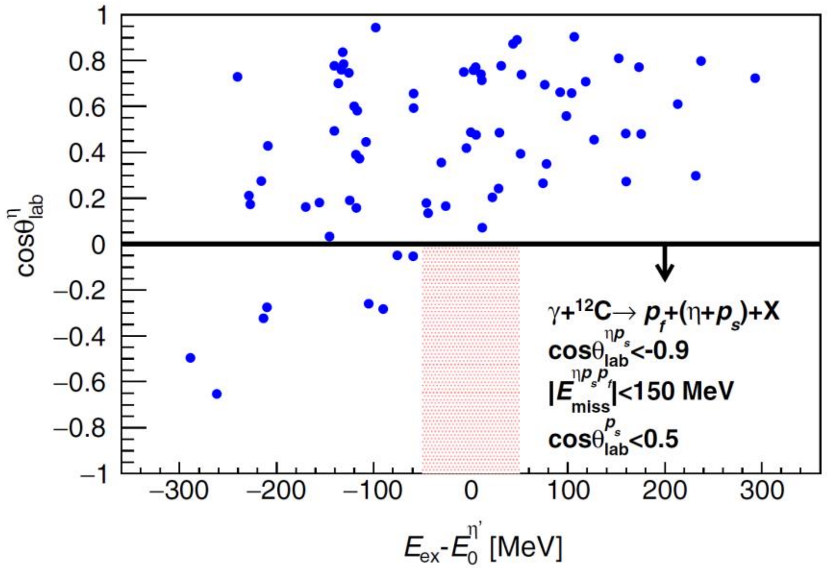
⇒ SBχS is expected to be **partially restored inside a nucleus**.

- **Search for η′ bound nuclei** [*N. Tomida et al., PRL 124 (2020) 202501*]

  $\gamma + {}^{12}\mathrm{C} \rightarrow \eta' \otimes {}^{11}\mathrm{B} + p$: missing mass spectroscopy by RPC-TOF

  $\eta' p \rightarrow \eta p$: Nuclear absorption signal at BGOegg

  for the first time!



No signal was observed.

⇒ $\frac{d\sigma}{d\Omega_{p_f}} < 2.2$ **nb/sr** (90%CL) for $\cos\theta_{lab}^{\eta p_s} < -0.9$

⇒ Comparison w/ **DWIA calculation**

Normalization by quasi-free η′

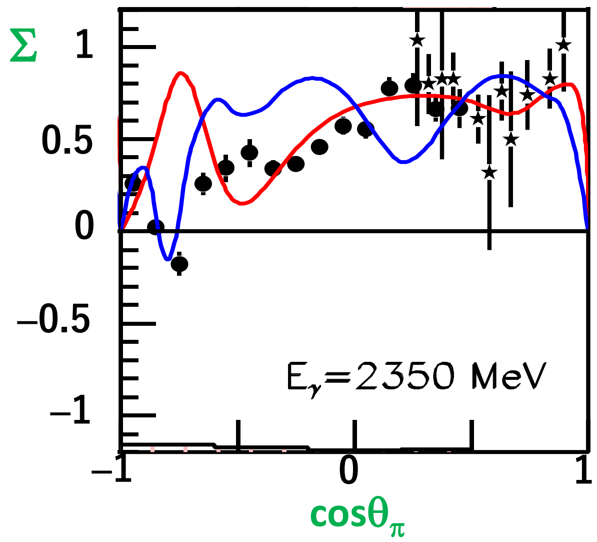
Large optical potential $|V_0| \geq 100$ MeV is unfavored.

- **Line shape analysis of η′ mass spectrum** in γγ invariant mass distribution [*Y. Matsumura's doctoral thesis (2021), Tohoku Univ.*]

Baryon resonance

- Meson photoproduction is suitable to study **excited baryons in s-channel** for understanding hadron structure **beyond the constituent quark model**.
- **π^0 photoproduction** : I=1 $\Rightarrow$ Both **N^*** and **Δ^*** contribution.
- **η / ω photoproduction** : Only **N^*** is relevant because of I=0. Especially, the η couples with the N^* including **$s\bar{s}$ quarks**.

  [π^0 : N. Muramatsu et al., PRC 100 (2019) 055202. η : T. Hashimoto & T. Nam, in preparation. ω : N. Muramatsu et al., PRC 102 (2020) 025201.]
- The measurement of **photon beam asymmetries** in addition to **differential cross sections** can **decompose overlapped resonances** by the interference of helicity amplitudes.



π^0 photon beam asymmetry (Σ)

● : BGOegg data

— : Bonn-Gatchina

— : GWU SAID

Σ@E_γ>2 GeV are new for all modes.

Future experiments with spins

Experiments using polarized γ and target

- We have carried out experiments using polarized photon beams at SPring-8 since 2000.

- **Many interesting or unknown phenomena** were found.

- Introducing a polarized HD target to SPring-8 experiments **upgrades the experiments to the next step**.

- **Many observables** obtained by the experiments are expected to clarify the unknown phenomena in the future.

16 observables for the $\gamma\, p \longrightarrow K\, Y$ reaction

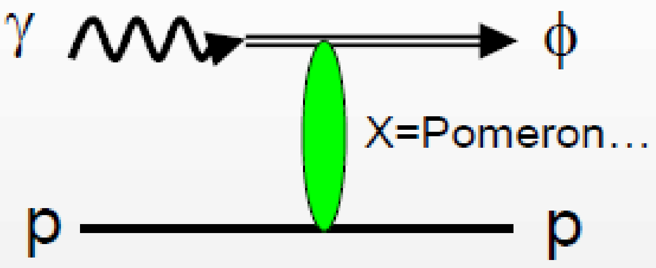
Complete measurements of all spin observables are possible

Observable		Beam	Target	Hyperon
Cross section & Single polarization				
1	$d\sigma/d\Omega$	-	-	-
2	Σ	linear	-	-
3	T	-	transverse	-
4	P	-	-	y
Beam-Target double polarization				
5	G	linear	z	-
6	H	linear	x	-
7	E	circular	z	-
8	F	circular	x	-

Observable		Beam	Target	Hyperon
Beam and Recoil hyperon double polarization				
9	Ox	linear	-	x
10	Oz	linear	-	z
11	Cx	circular	-	x
12	Cz	circular	-	z
Target and Recoil hyperon double polarization				
13	Tx	-	x	x
14	Tz	-	x	z
15	Lx	-	z	x
16	Lz	-	z	z

ϕ meson photoproduction on proton LEPS cross section data

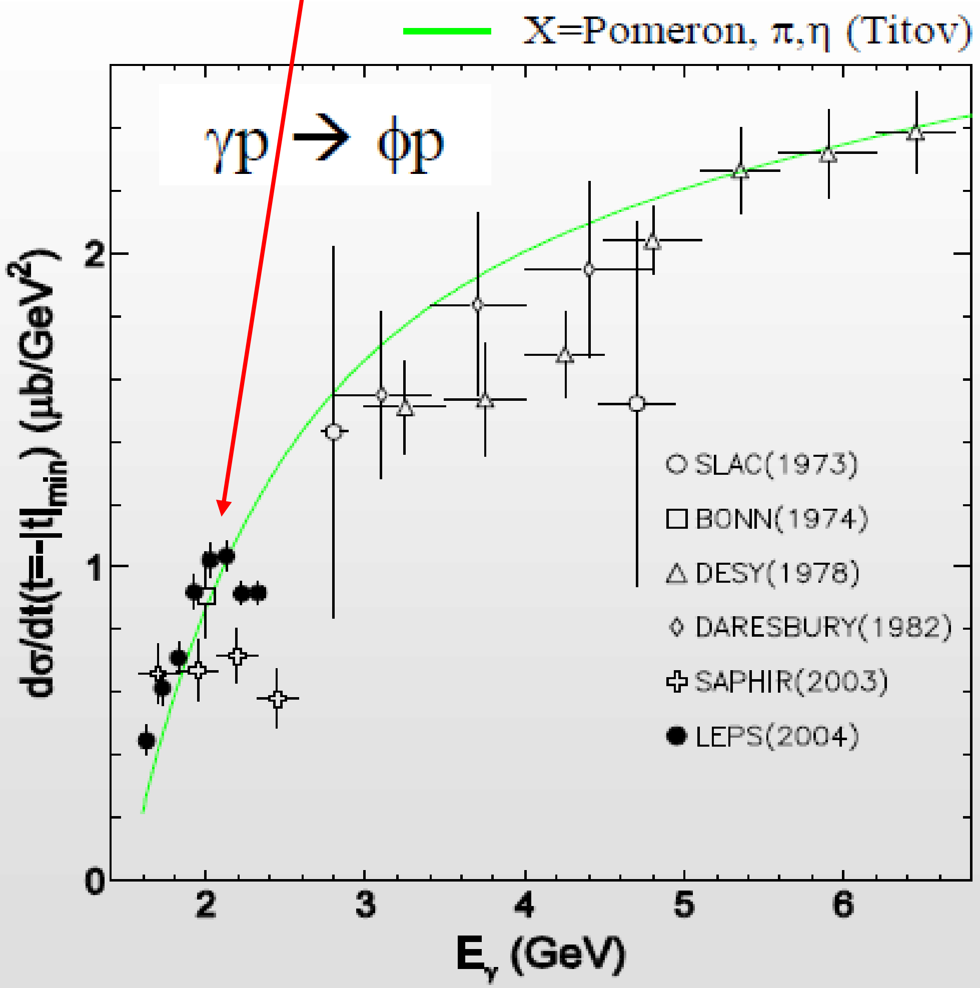
Diffractive ϕ meson photoproduction on proton



E_γ dependence is not understood by the theory

LEPS/SAPHIR inconsistency

Bump structure was observed.



T. Mibe *et al*. Phys. Rev. Lett. 95 182001 (2005)

Multiquark physics

SPring-8/LEPS group reported evidence for **5 quark state (θ^+)** in 2003 and 2009.
Several groups also reported the evidence, however it disappeared after taking high statistics data.
SPring-8/LEPS group took additional data and data analysis will finish soon.

These results inspired extensive search for 4 quark and 5 quark states in the world.

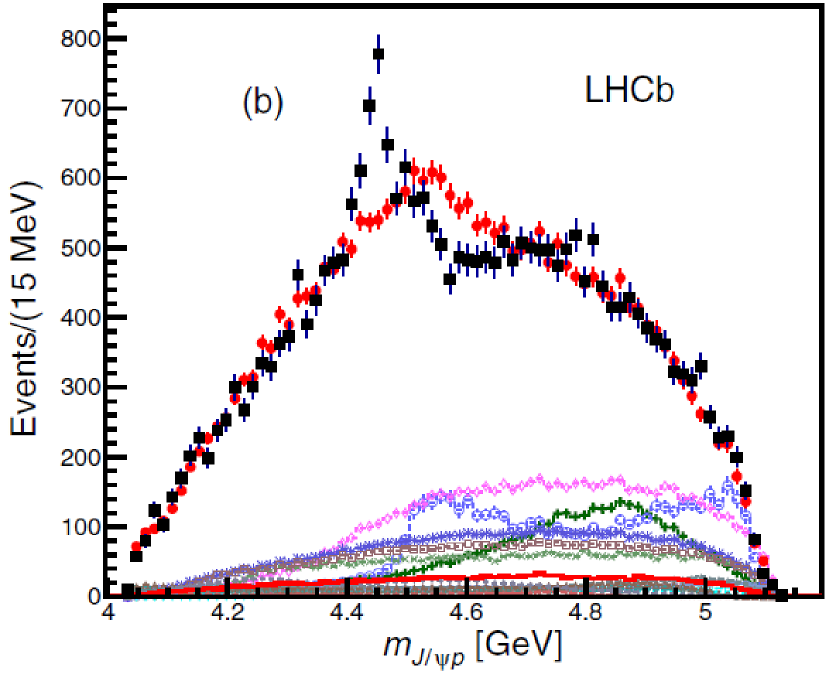
Belle, BaBar, and BESIII reported evidence for **4 quark states**, called X, Y, and Z.

LHCb reported evidence for **5 quark states**, called Pc.

LHCb reported evidence for 3 penta quark states with $c\bar{c}$

$\Lambda_b^0 \to J/\psi\, p\, K^-$ $J/\psi\, p$ invariant mass

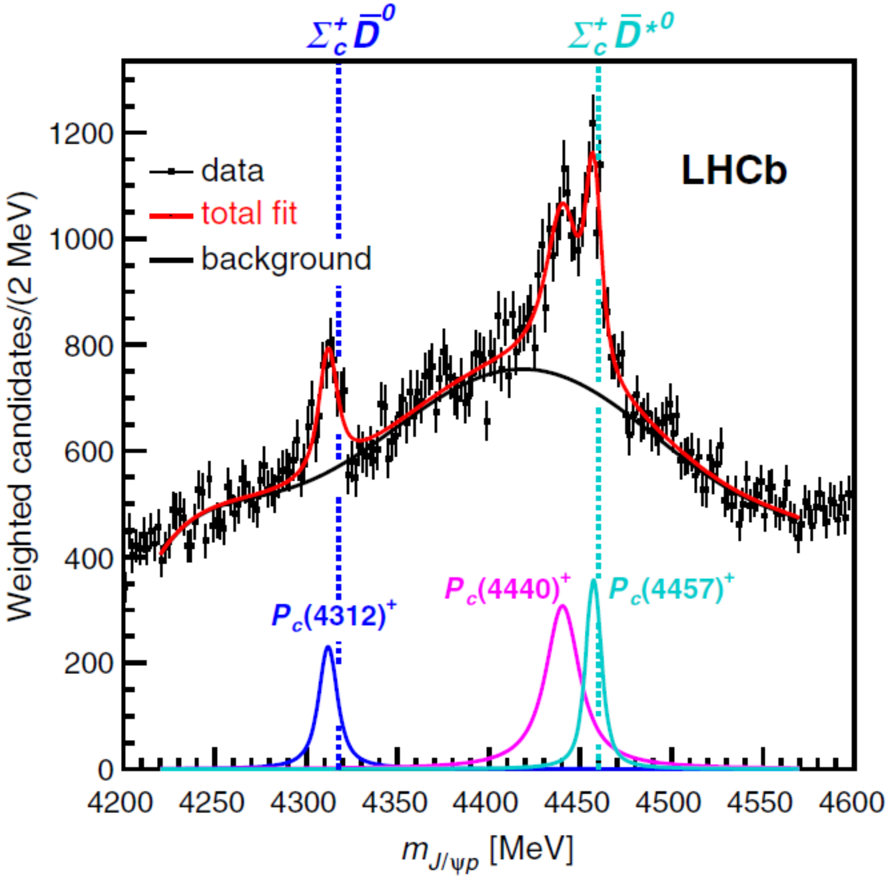
pp collision energy = 7 and 8 TeV



R. Aaij et al. (LHCb Collaboration)
Phys. Rev. Lett. 115 (2015) 072001

pp collision energy = 7, 8, and 13 TeV

Three states are discovered.



R. Aaij et al. (LHCb Collaboration)
Phys. Rev. Lett. 122 (2019) 222001

It is natural that 3 penta quark states with $s\bar{s}$ and $b\bar{b}$ also exist

Y.H. Lin, C.W. Shen B.S. Zou, NP980, 21 (2018)

Decay behavior of Ps

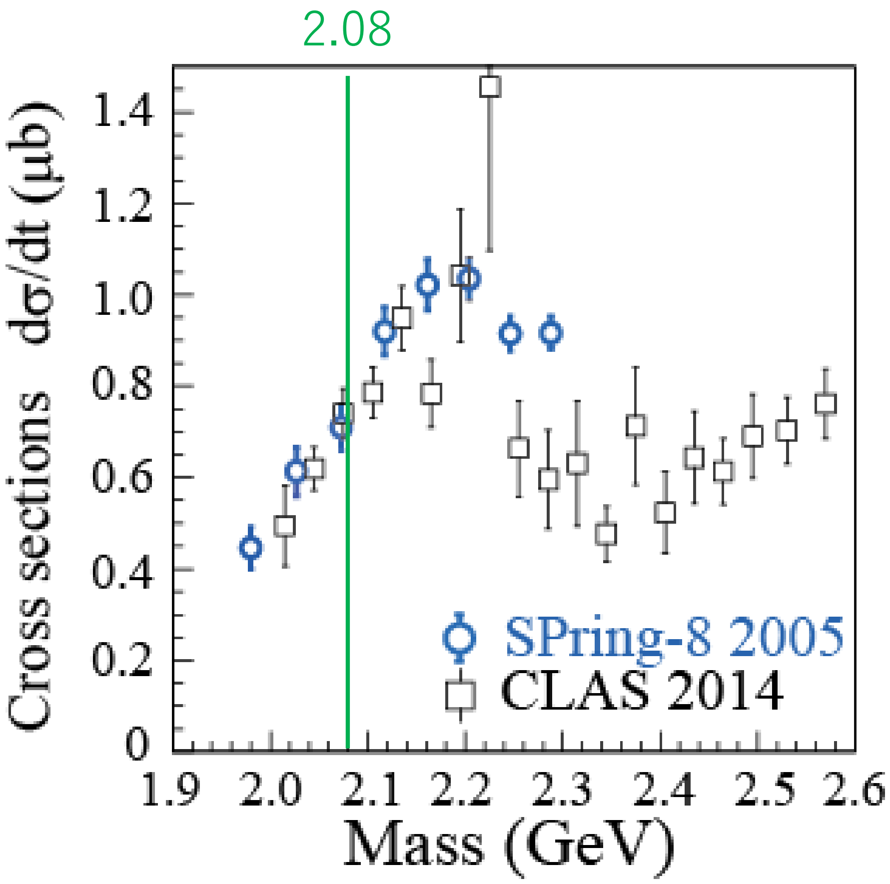
Mode	Widths (MeV)		
	$J^P=3/2^-$	$J^P=3/2^-$	$J^P=1/2^-$
	$N(1875)\ K\Sigma^*$	$N(2080)\ K^*\Sigma$	$N(2080)\ K^*\Sigma$
$N\sigma(500)$	1.5	0.05	0.3
πN	0.2	0.2	27.0
ρN	1.4	3.3	7.3
ωp	4.0	10.0	21.7
$K\Sigma$	0.02	1.3	10.9
$K\Lambda$	0.4	3.3	23.0
ηp	0.4	0.3	2.1
$\pi\Delta$	117.3	73.8	55.5
$K^*\Lambda$	–	2.1	9.5
ϕp	–	17.0	32.2
$K\Sigma^*$	–	6.5	1.6
$K\Lambda(1520)$	–	0.04	0.5
$K\Lambda(1405)$	–	2.4	3.6
$K\pi\Lambda$	10.1	–	–
$K\pi\Sigma$	–	20.8	23.1
Total	135.2	141.1	218.1

Decay behavior of Pb

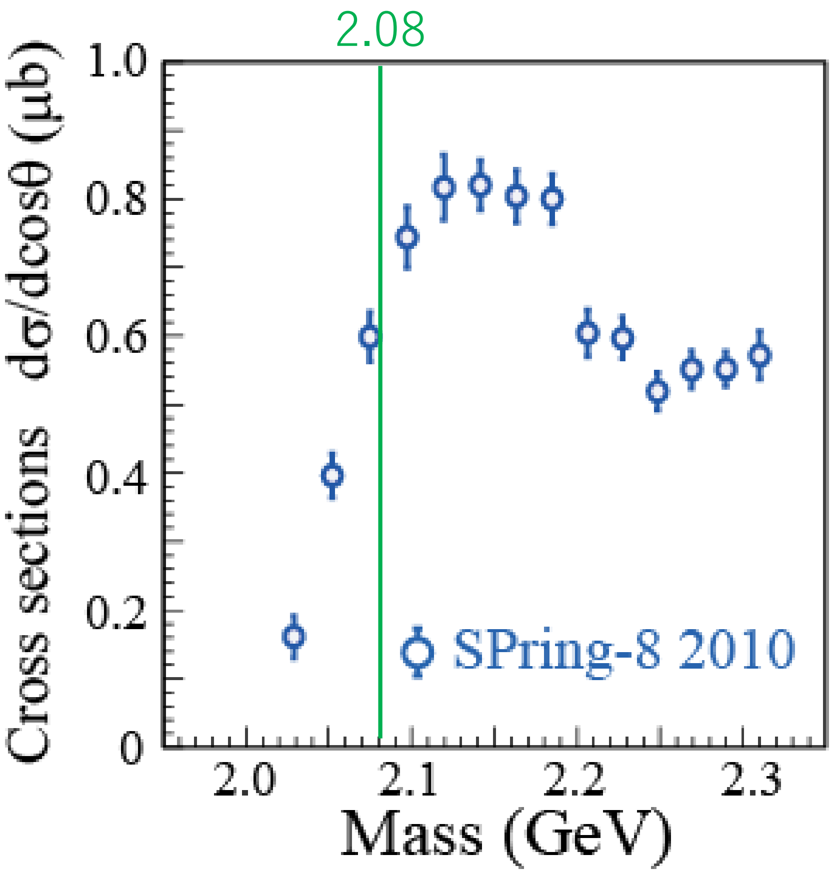
Mode	Widths (MeV)		
	$J^P=3/2^-$	$J^P=3/2^-$	$J^P=1/2^-$
	$B\Sigma_b^*$	$B^*\Sigma_b$	$B^*\Sigma_b$
$B^*\Lambda_b$	271.1	19.9	167.3
Υp	0.3	0.04	0.1
ρN	10.4	0.02	0.1
ωp	39.5	0.07	0.4
$B\Lambda_b$	–	7.3	136.1
$B\Sigma_b$	–	–	–
$\eta_b p$	0.02	0.0001	0.0009
$\chi_{b0} p$	1.4	0.0008	0.2
πN	0.05	0.005	0.003
$B\Sigma_b^*$	–	–	–
Total	322.7	27.4	304.2

SPring-8/LEPS group has already reported existence of 2 bump structures

γ p -> ϕ p ($s\bar{s}$ + uud)



γ p -> K^+ Λ(1520) ($u\bar{s}$ + uds)



T. Mibe et al., Phys. Rev. Lett. 95, 182001 (2005)
B. Dey et al., Phys. Rev. C 89, 055208 (2014)

H. Kohri et al., Phys. Rev. Lett. 104, 172001 (2010)

Helicity dependence of Ps excitations

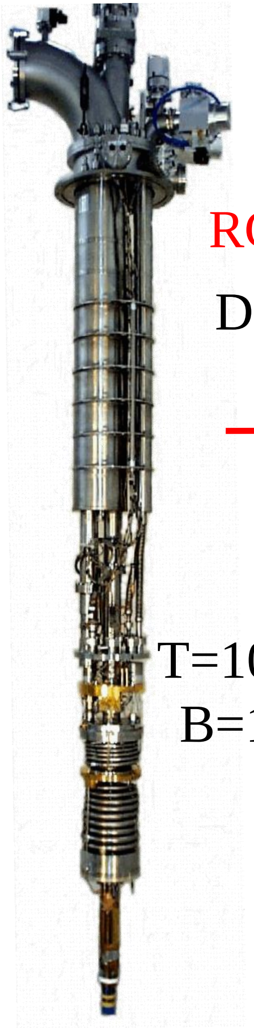
Ps states are expected to have $1/2^-$ and $3/2^-$.

Helicity dependence is a key to determine the spin-parity of the bump.

Photon beam	Target	Helicity	
→	←	1/2	Helicity=1/2 excites both $1/2^-$ and $3/2^-$
→	→	3/2	Helicity=3/2 strongly excites $3/2^-$ does not excite $1/2^-$

Development of Polarized HD target

Refrigerators for polarized HD target



RCNP

DRS

T=10 mK
B=17 T

RCNP

TC1

T=4K
B=0.2T

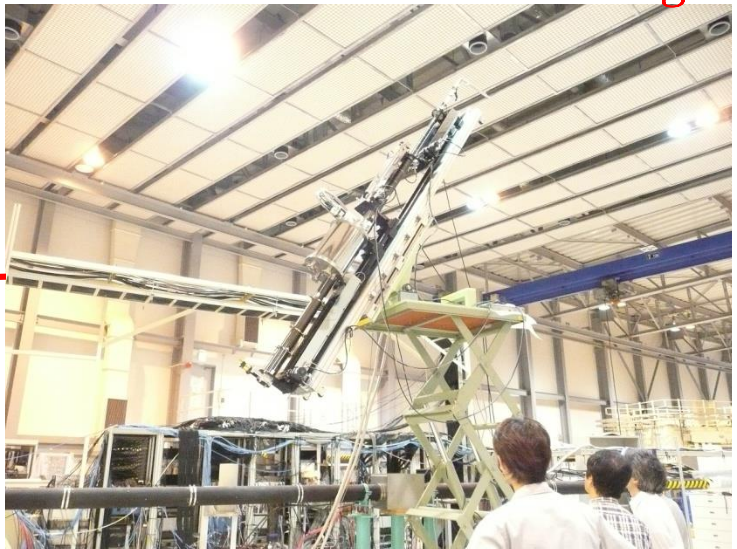
RCNP -> SPring-8

SC

T=2K
B=1T

TC2 T=4K B=0.2T

SPring-8

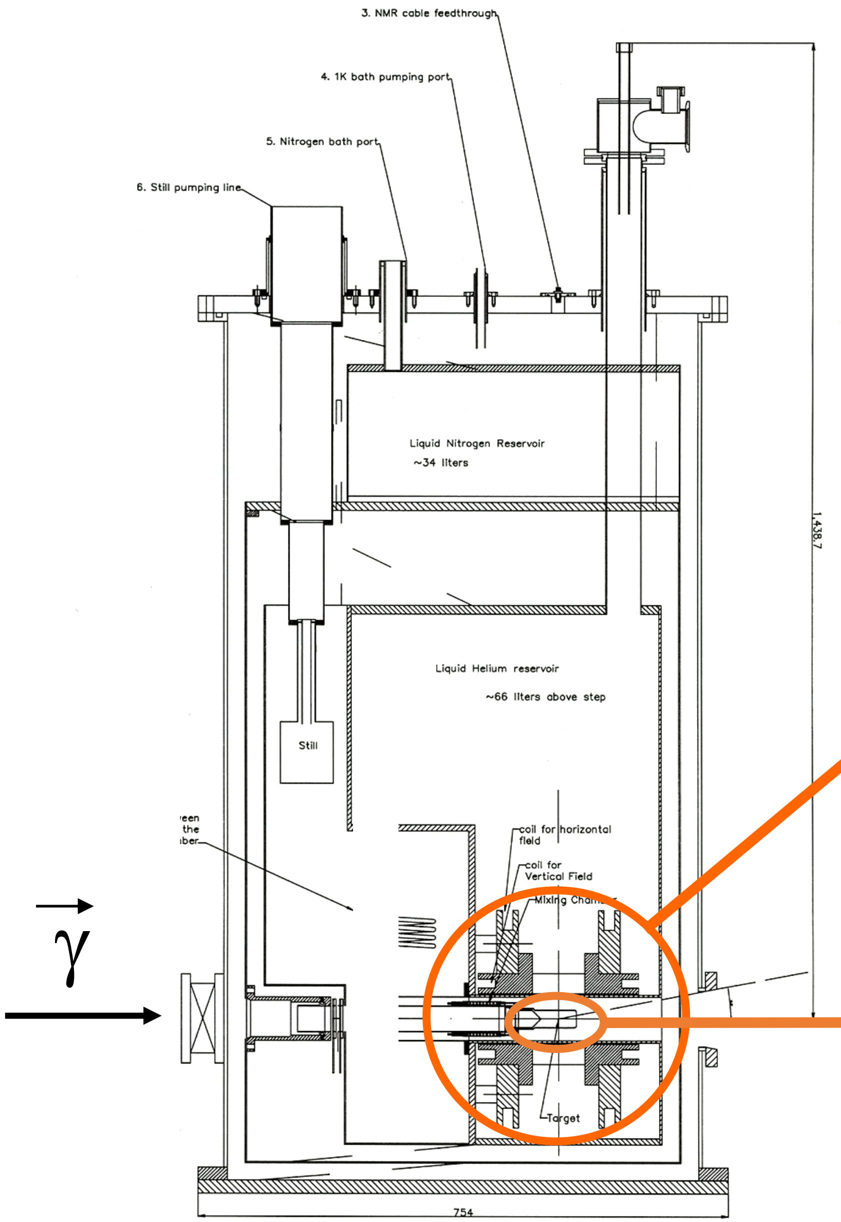


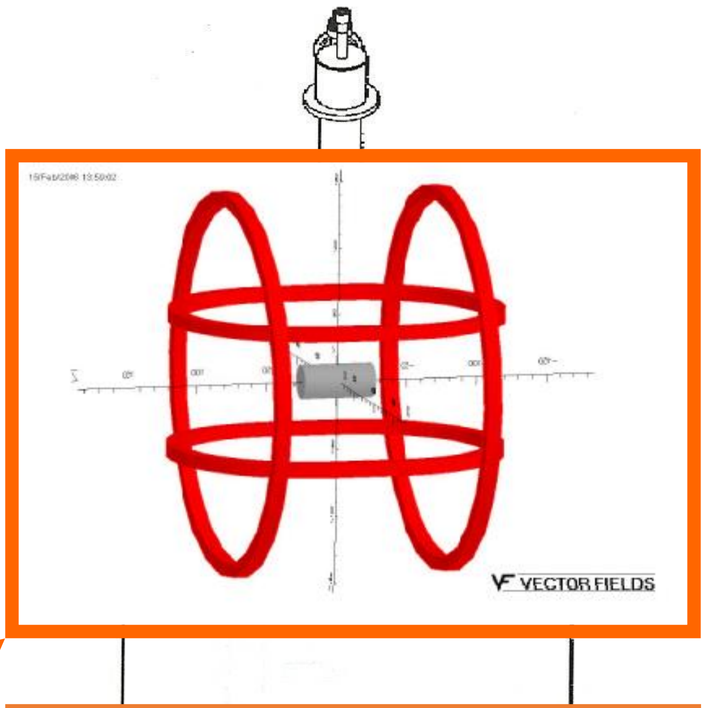
IBC

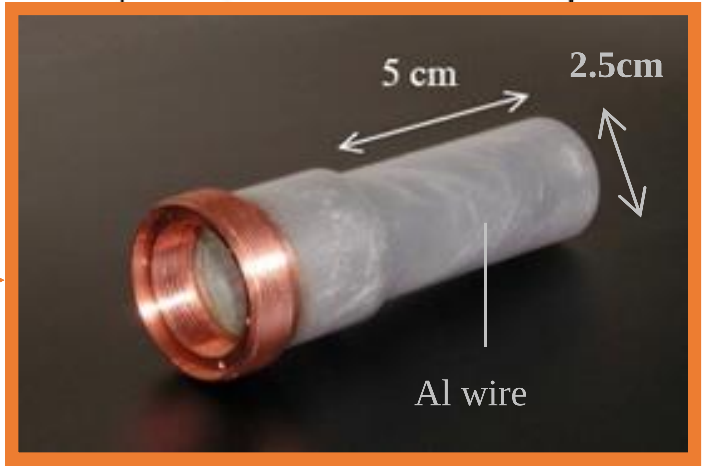
T=300 mK
B=1 T

SPring-8

IBC(In Beam Cryostat)







Combination of beam and target polarizations provides various physics observables.

Rich information on hadron photoproduction can be obtained.

γ beam Circular or Linear

Target Longitudinal or Transverse

Introduction of polarized HD target to LEPS

For further spin studies, we introduced a polarized HD target.
We started developing the HD target in 2005.

Historically, the HD target had been developed by BNL/LEGS(USA) group and ORSAY(France) group for more than 10 years.
ORSAY group finished the development in 2005 and their knowledge and some equipments were imported to RCNP, Osaka university group.

To introduce the polarized HD target will upgrade the LEPS experiment to the next step.

Characteristics of polarized HD target

Polarization method

HD target is polarized by the static method using “brute force”
at low temperature (10 mK) and high magnetic field (17 Tesla).
It takes about 2-3 months to polarize the target.

Advantage and disadvantage

HD molecule does not contain heavy nuclei such as Carbon and Nitrogen.
HD target needs thin aluminum wires (at most 20% in weight) to
insure the cooling.

Polarization

H : 90 % D : 60 %

Relaxation Time

About 1 year at 300 mK and 1 Tesla during the experiment.

Boltzmann law of statistical mechanics

$N_- = N \exp(-E_-/kT)$

$N_+ = N \exp(-E_+/kT)$

$N_-/N_+ = \exp((E_- - E_+)/kT)$

$\quad = \exp(\Delta E/kT)$

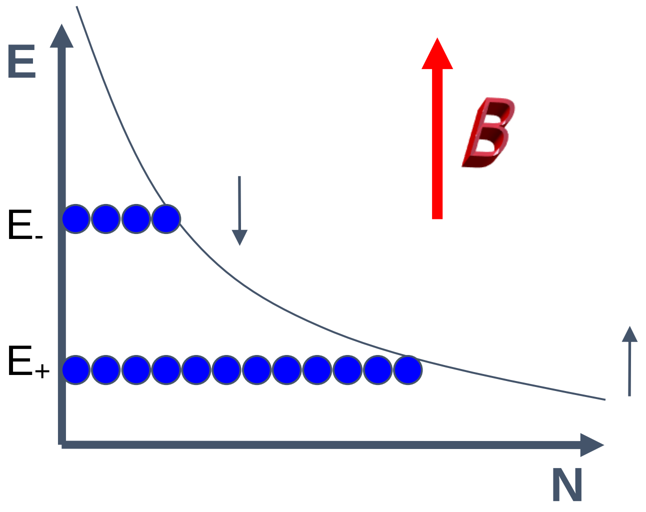
$\quad = \exp(2\mu_p B/kT)$

k: Boltzmann constant

μ_p: Proton magnetic moment

B: Magnetic field

T: Temperature



Proton polarization

$P = (N_+ - N_-)/(N_+ + N_-)$

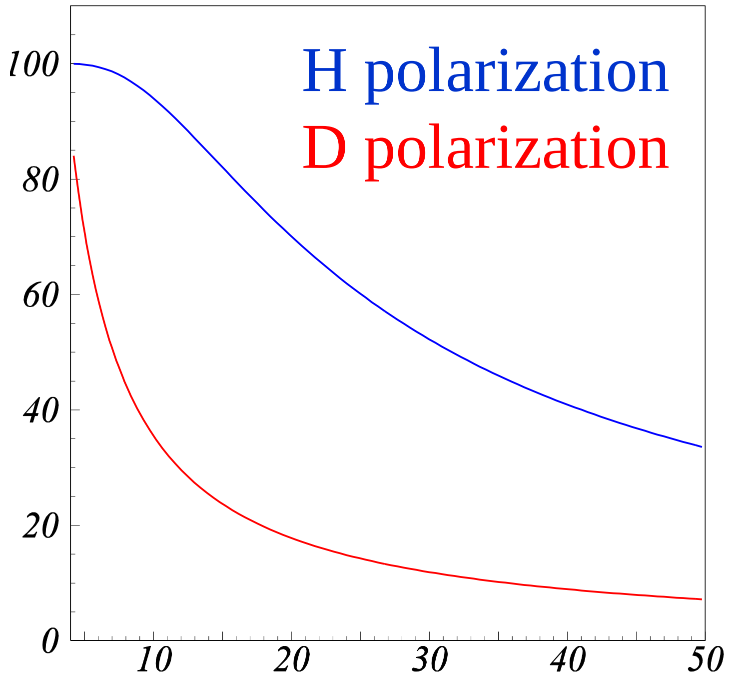
$\quad = \tanh(\mu_p B/kT)$

In case of B = 17 Tesla, T = 10 mK,

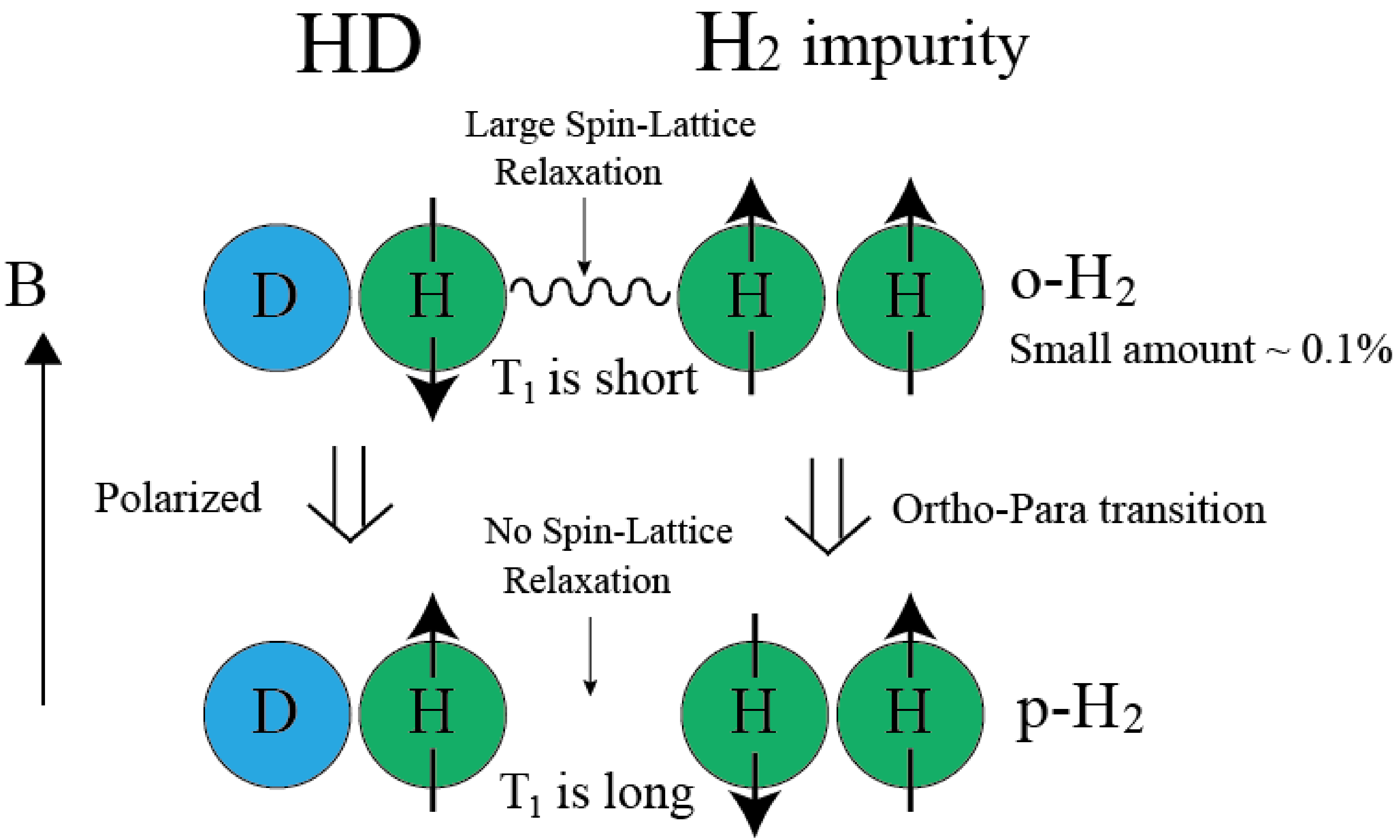
P ~ 90%

D polarization is small because $\mu_D < \mu_p$

Polarization (%) at 17 Tesla



Principle of polarized HD target

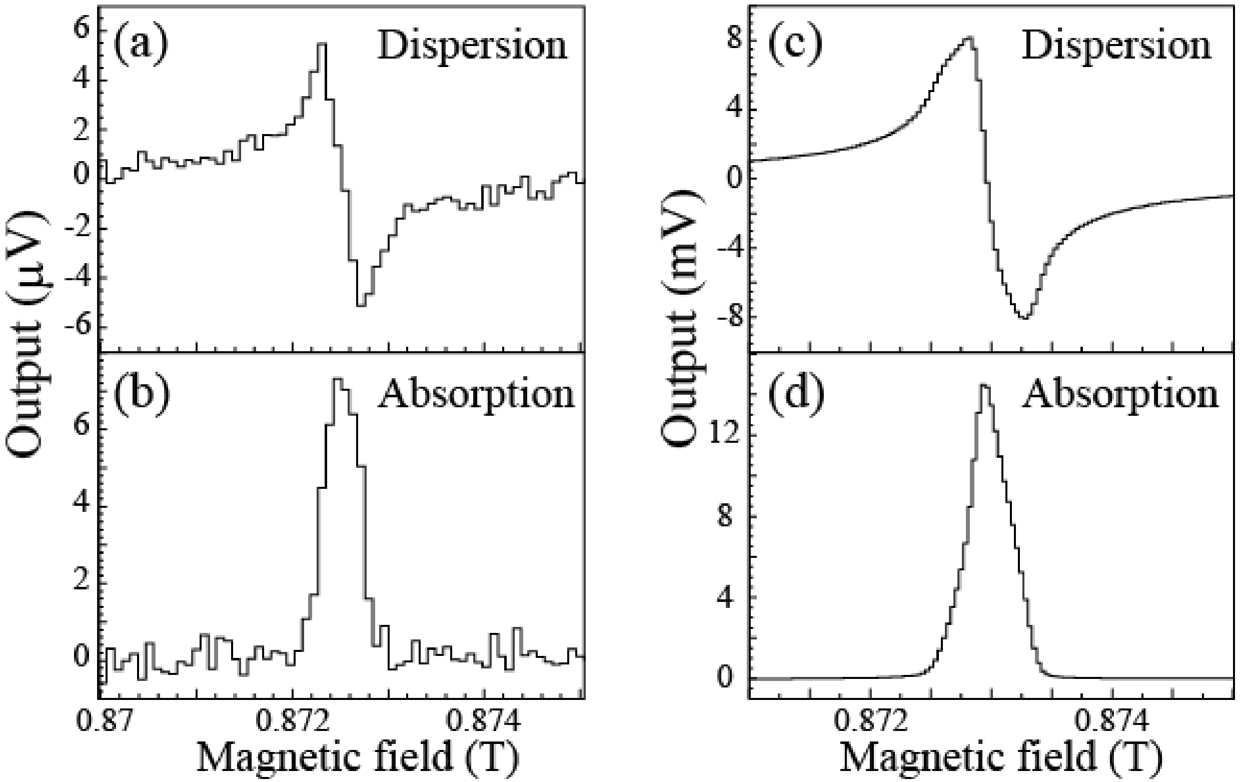


Polarization is frozen.

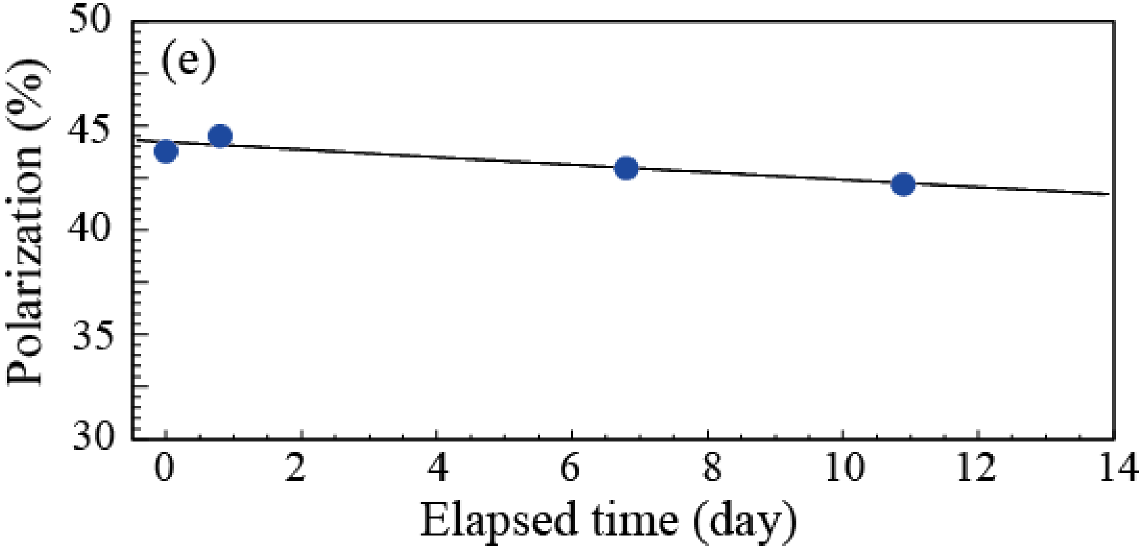
H-NMR signals before and after the aging for 3 months

Before the aging

After the aging



Relaxation of the H polarization after the aging for 3 months



Thermal Equilibrium at 4.2 K and 0.87 T → ~2000 times larger

P_H = 44 +- 1 %

T_1 = 8+-2 months

Publication of polarized HD target developments

1. Development of portable **NMR polarimeter system** for polarized HD target
   T. Ohta et al. Nuclear Instruments and Methods A 633, 46 (2011)

2. HD gas analysis with **gas chromatography and quadrupole mass spectrometer**
   T. Ohta et al. Nuclear Instruments and Methods A 640, 241 (2011)

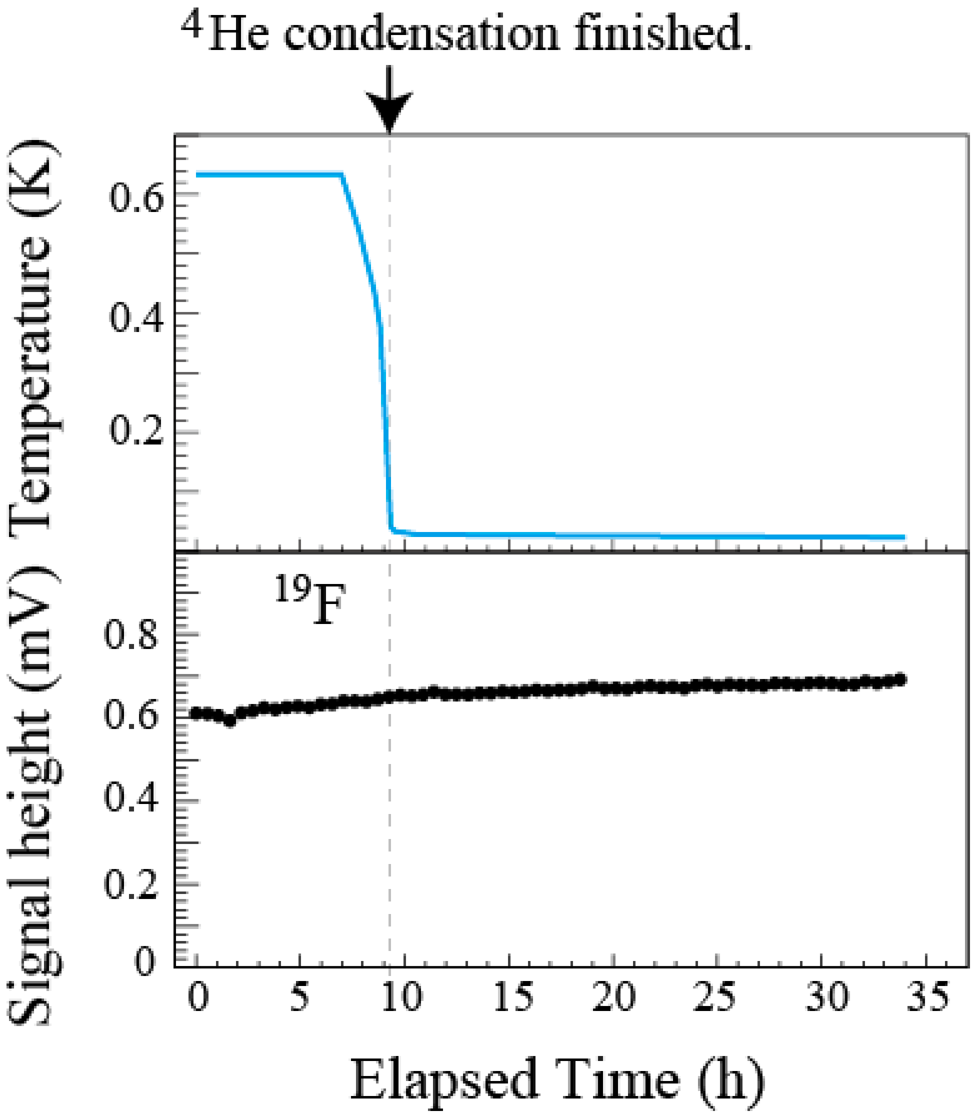
3. **Distillation** of hydrogen isotopes for polarized HD targets
   T. Ohta et al. Nuclear Instruments and Methods A 664, 347 (2012)

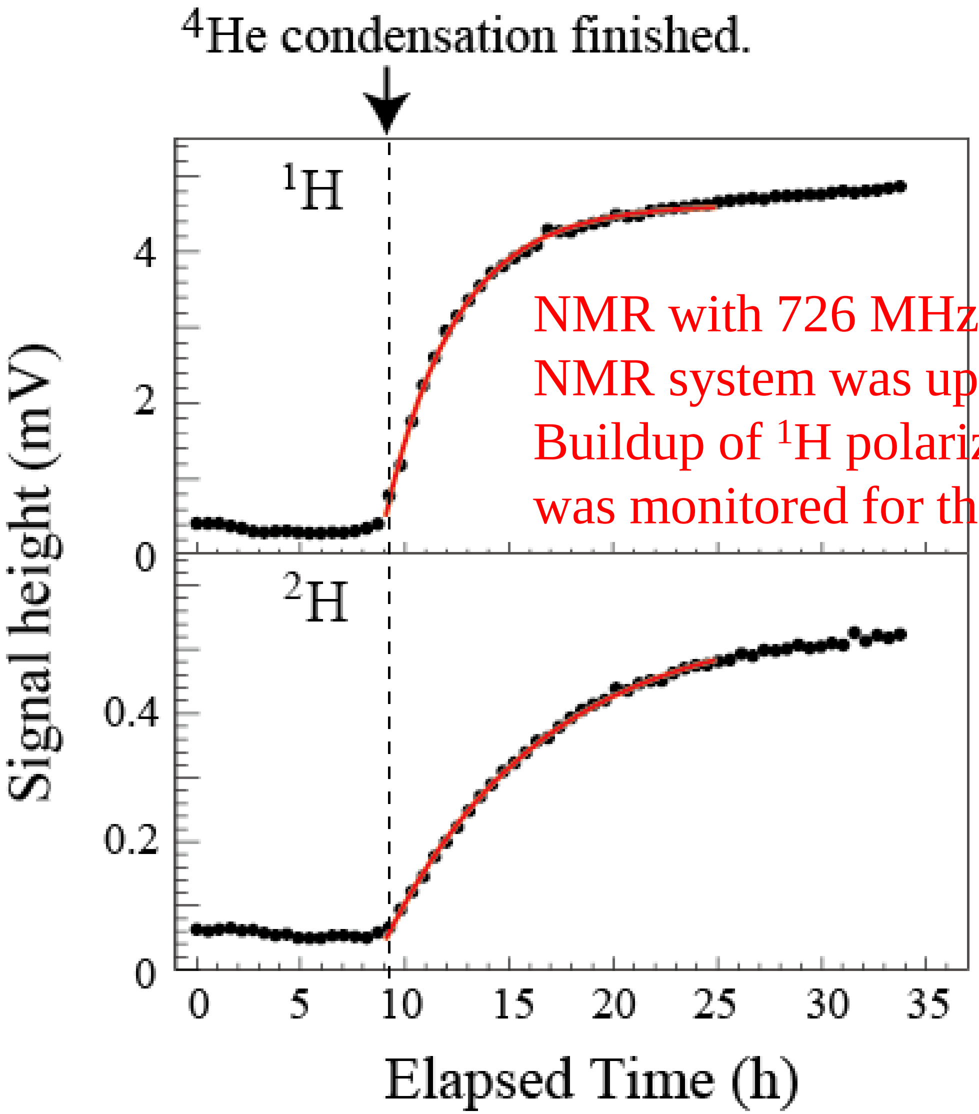
4. Anisotropic thermal conductivity of **hydrogen deuteride crystal** for polarized proton target development
   M. Utsuro et al. Physica B 418, 36 (2013)

5. **Monitoring the buildup of hydrogen polarization** for polarized hydrogen-deuteride (HD) targets with nuclear magnetic resonance (NMR) **at 17 T**
   T. Ohta et al. Review of Scientific Instruments 91, 095104 (2020)

Monitoring the buildup of hydrogen polarization for polarized HD targets with NMR at 17 T

Review of Scientific Instruments 91, 095104 (2020)





$T_1 \sim 3$ h

NMR with 726 MHz
NMR system was upgraded.
Buildup of ^{1}H polarization was monitored for the first time.

$T_1 \sim 8$ h

Status of polarized HD target and future plan

- We are developing a polarized HD target for the near future LEPS experiments using polarized photon beams and HD targets.
  We will be able to obtain rich information to understand hadron photoproduction.

- The polarization of H is **44+-1%** and the relaxation time of the H polarization is **8+-2 months**.
  These performances are good enough for physics runs.

- SPring-8 experiments with spin are complementary to J-PARC experiments.
  SPring-8(8 GeV) will be downgraded to SPring-8-II(6 GeV).
  I want to continue the experiments with spin after SPring-8-II.

Thank you very much