重陽子テンソル偏極標的とHERMESの結果

＋α

Measurement of the Tensor Structure Function b_1 of the Deuteron

A. Airapetian et al, Phys. Rev. Lett. 95 (2005) 242001, 6pp

The HERMES Polarized Hydrogen and Deuterium Gas Target in the HERA Electron Storage Ring

A. Airapetian et al, Nucl. Instr. and Meth. A540 (2005) 68

山形大　宮地義之

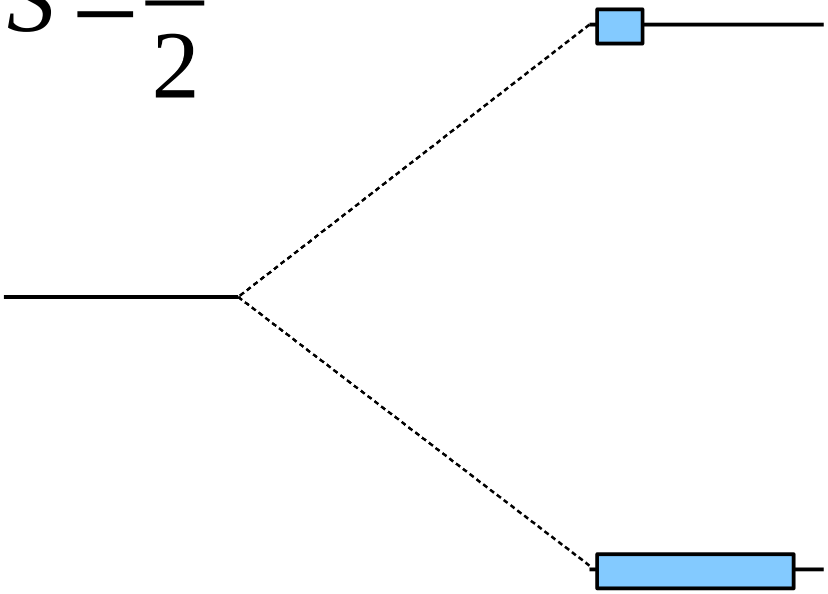
内容

- 重陽子のスピン偏極
  - ベクトル偏極とテンソル偏極
- HERMESでの重陽子テンソル構造関数 b_1 測定
  - 実験装置
    - 重陽子テンソル偏極標的について
  - 構造関数 b_1 測定結果
- 重陽子テンソル偏極**固体標的**の可能性
  - 将来計画
- まとめ

重陽子のスピン偏極

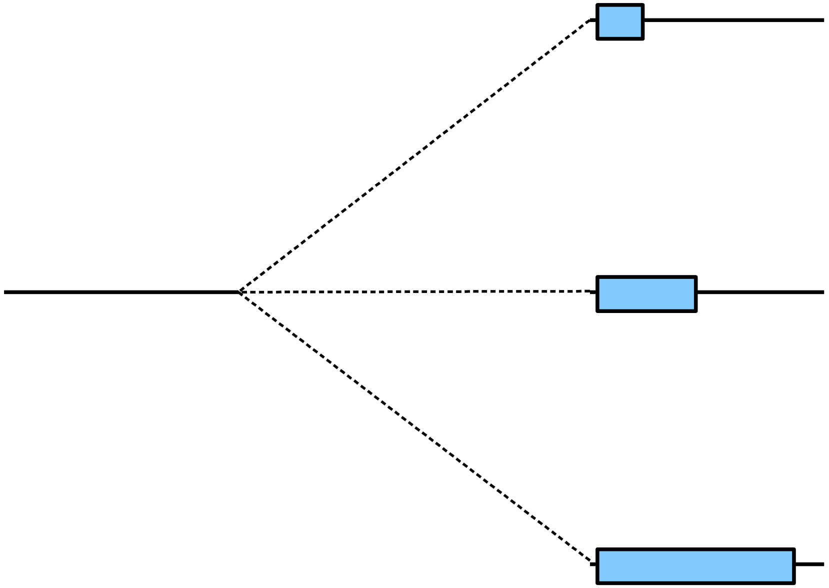
陽子

$$S=\frac{1}{2}$$

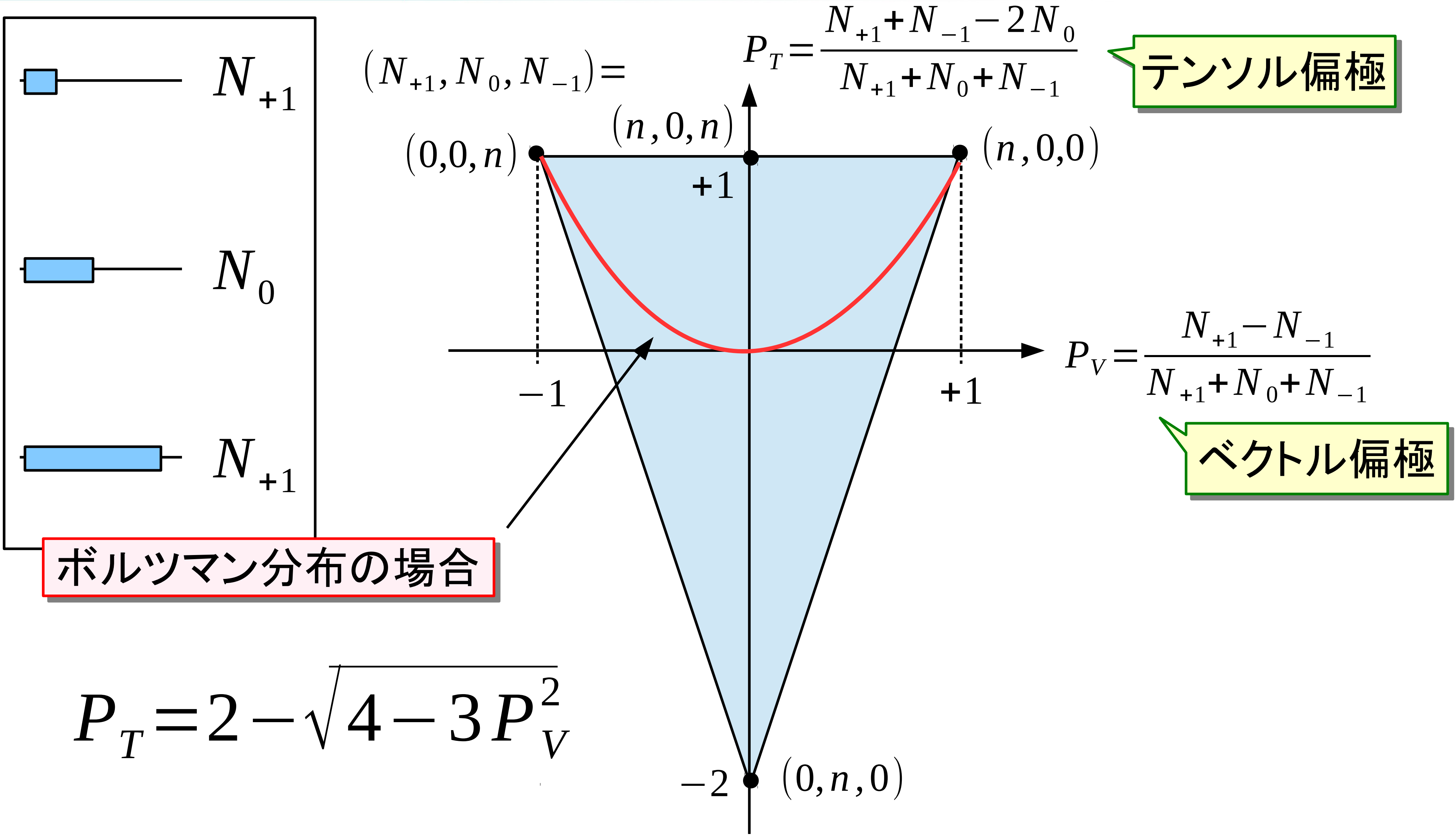


重陽子

$$S=1$$



重陽子のスピン偏極： ベクトル vs テンソル



$$P_T = \frac{N_{+1} + N_{-1} - 2N_0}{N_{+1} + N_0 + N_{-1}}$$

テンソル偏極

$$P_V = \frac{N_{+1} - N_{-1}}{N_{+1} + N_0 + N_{-1}}$$

ベクトル偏極

ボルツマン分布の場合

$$P_T = 2 - \sqrt{4 - 3P_V^2}$$

ベクトル偏極、テンソル偏極：　ボルツマン分布

$$S=1$$

$$P_V=\frac{4\tanh x}{3+\tanh^2 x}$$

$$P_T=\frac{4\tanh^2 x}{3+\tanh^2 x}$$

$$x=\frac{\mu B}{2kT}$$

$$P_T=2-\sqrt{4-3P_V^2}$$

具体的な値

$$(P_V, P_T)=\begin{matrix}(0.3, 0.07)\\(0.4, 0.12)\\(0.5, 0.2)\end{matrix}$$

HERMESでの構造関数 b_1 測定

Beam: HERA electron / positron beam

27.6 GeV/c

longitudinally pol. (up to 65%)

Target:

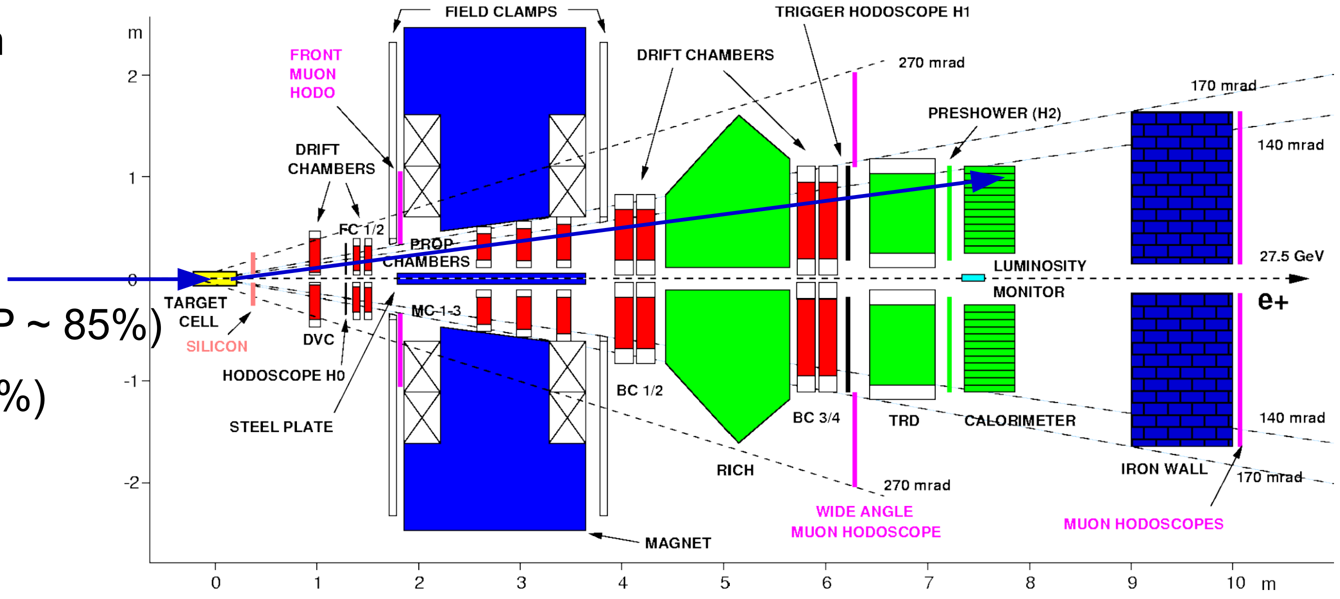
Longitudinally polarized H, **D** (P ~ 85%)

Transversely polarized H (P ~ 75%)

Unpolarized H, D, Nuclei

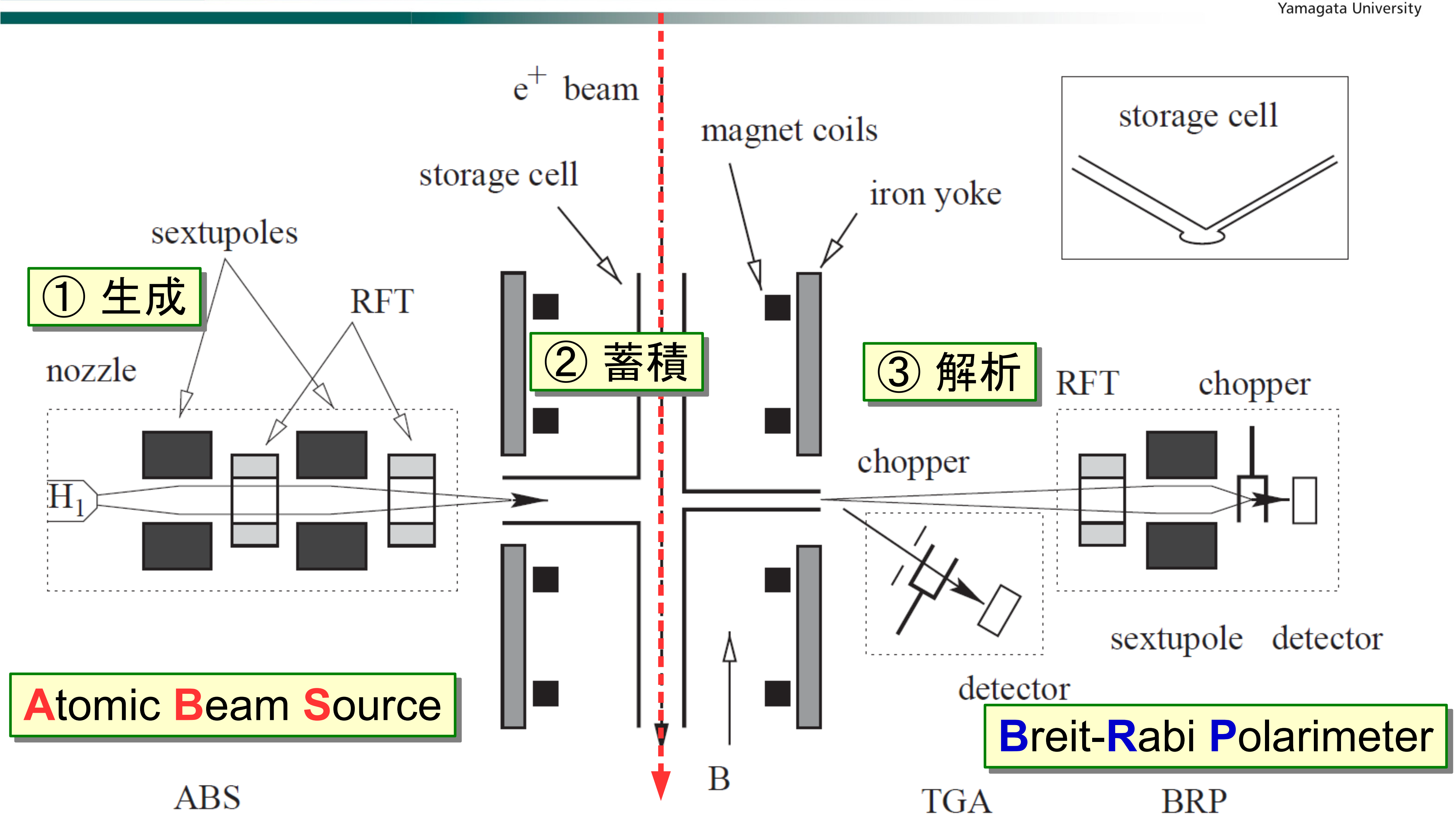
Detector:

- track reconstruction
    - momentum resolution < 2%
- **lepton identification**
    - hadron contamination < 1%
- **hadron identification (pi,K,p)**
    - RICH, 2 < p < 15 (GeV/c)
- recoil nucleon was not detected



$$e+\vec{d}\rightarrow e'+X$$

HERMES重陽子ガス標的



① 生成

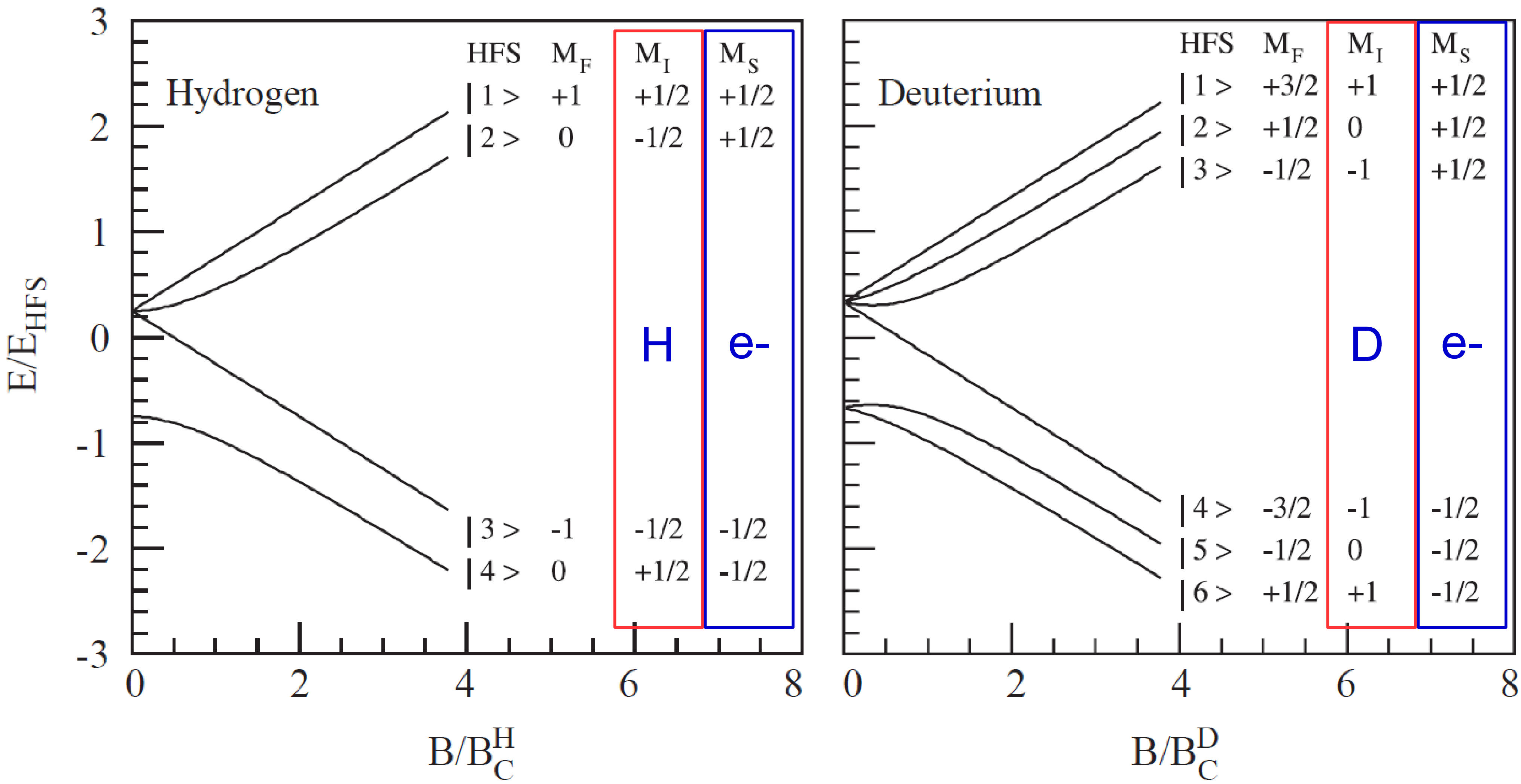
② 蓄積

③ 解析

Atomic Beam Source

Breit-Rabi Polarimeter

Hyper-fine energy levels
Hydrogen (Deuterium) Atoms

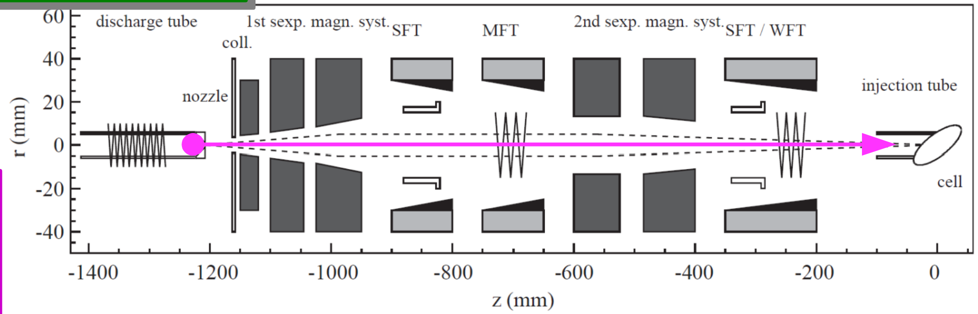


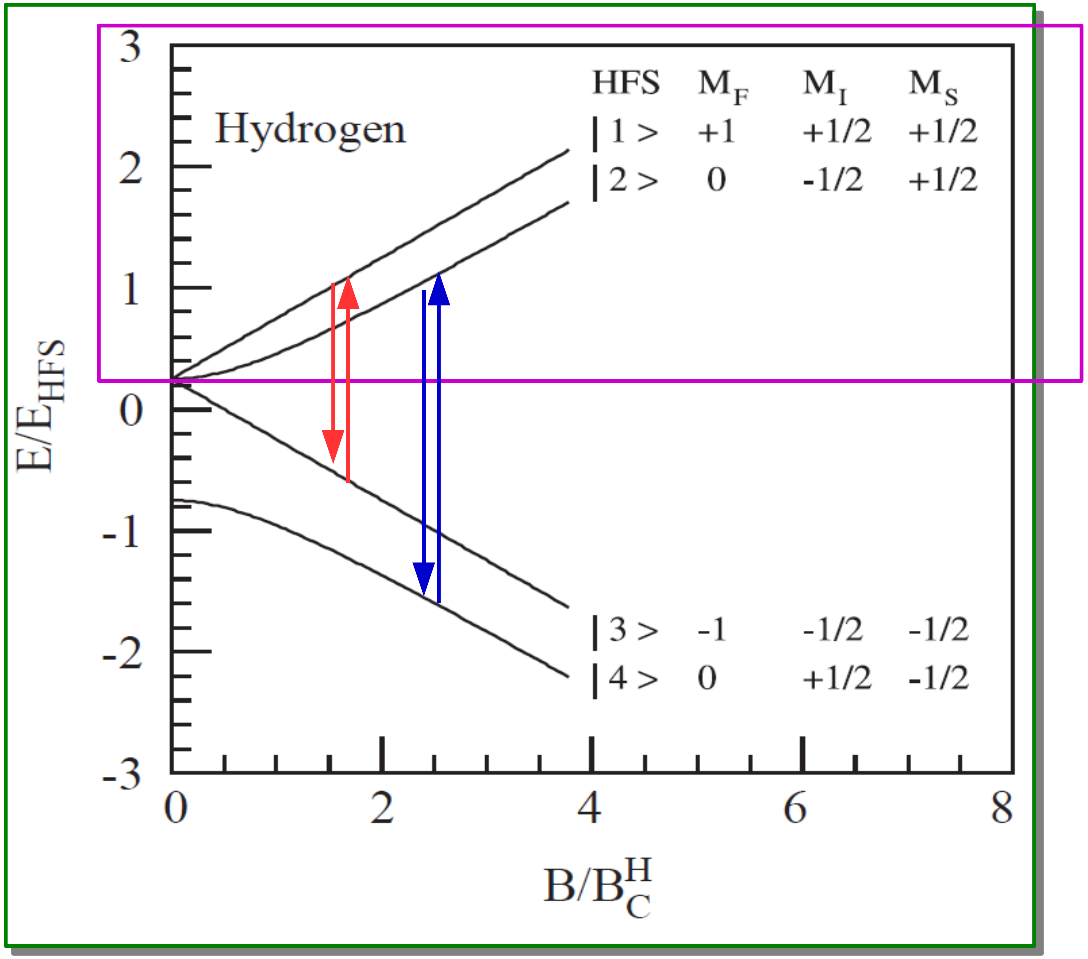
HFS	M_F	M_I	M_S
|1 >	+1	+1/2	+1/2
|2 >	0	-1/2	+1/2
|3 >	-1	-1/2	-1/2
|4 >	0	+1/2	-1/2

HFS	M_F	M_I	M_S
|1 >	+3/2	+1	+1/2
|2 >	+1/2	0	+1/2
|3 >	-1/2	-1	+1/2
|4 >	-3/2	-1	-1/2
|5 >	-1/2	0	-1/2
|6 >	+1/2	+1	-1/2

偏極手法

ABS概要





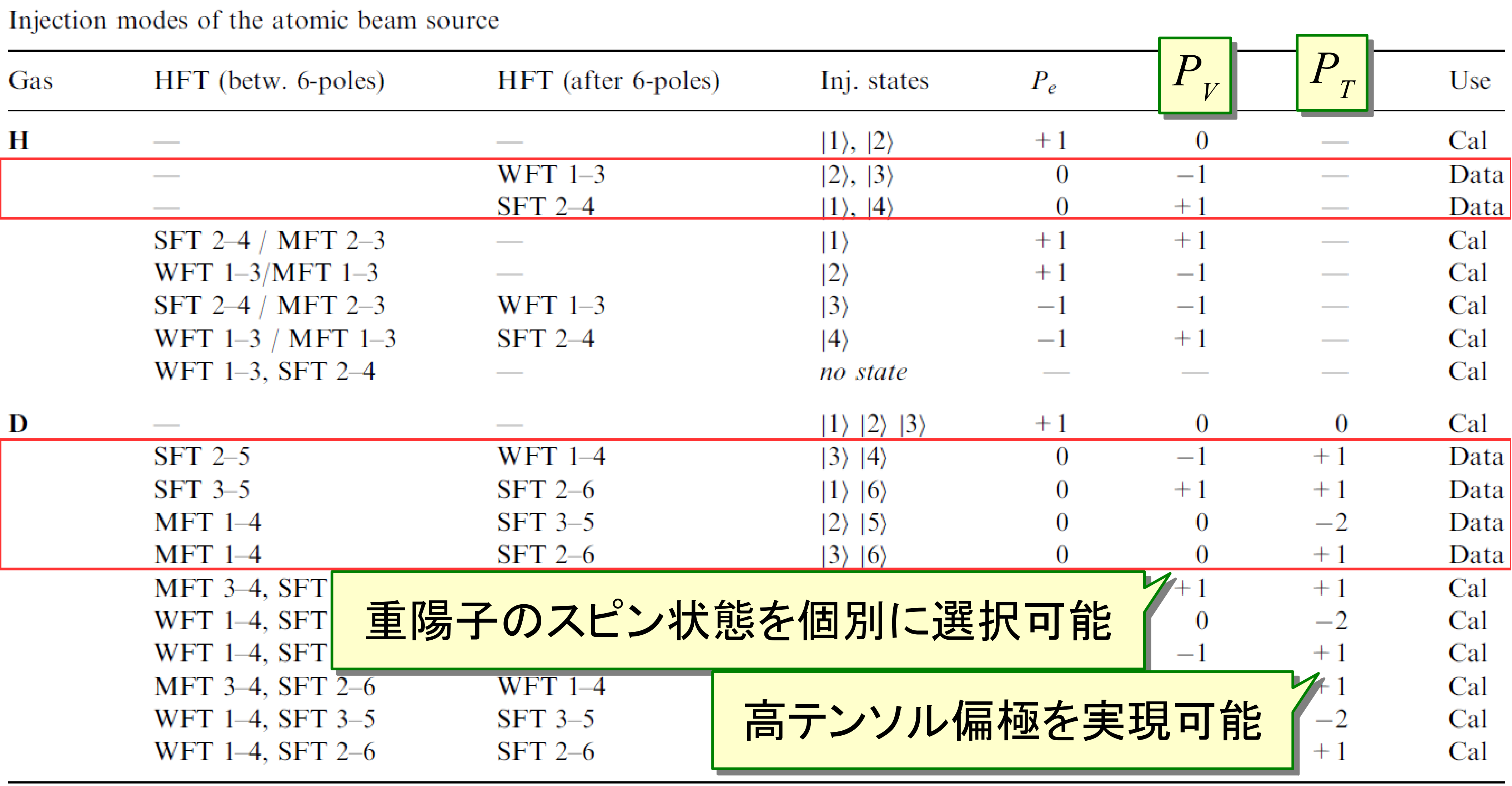
$$M_S=+\frac{1}{2}$$ のみを通過 $P_V=0$

$1 \leftrightarrow 3 \quad |2\rangle, |3\rangle \quad P_V=-1$

$2 \leftrightarrow 4 \quad |1\rangle, |4\rangle \quad P_V=+1$

$P^{\mathrm{injection}}$ ~ 0.97 (H), 0.91 (D)

ABS Injection Mode



Injection modes of the atomic beam source

Gas	HFT (betw. 6-poles)	HFT (after 6-poles)	Inj. states	P_e	P_V	P_T	Use
H	—	—	|1⟩, |2⟩	+1	0	—	Cal
	—	WFT 1–3	|2⟩, |3⟩	0	−1	—	Data
	—	SFT 2–4	|1⟩, |4⟩	0	+1	—	Data
	SFT 2–4 / MFT 2–3	—	|1⟩	+1	+1	—	Cal
	WFT 1–3/MFT 1–3	—	|2⟩	+1	−1	—	Cal
	SFT 2–4 / MFT 2–3	WFT 1–3	|3⟩	−1	−1	—	Cal
	WFT 1–3 / MFT 1–3	SFT 2–4	|4⟩	−1	+1	—	Cal
	WFT 1–3, SFT 2–4	—	*no state*	—	—	—	Cal
D	—	—	|1⟩ |2⟩ |3⟩	+1	0	0	Cal
	SFT 2–5	WFT 1–4	|3⟩ |4⟩	0	−1	+1	Data
	SFT 3–5	SFT 2–6	|1⟩ |6⟩	0	+1	+1	Data
	MFT 1–4	SFT 3–5	|2⟩ |5⟩	0	0	−2	Data
	MFT 1–4	SFT 2–6	|3⟩ |6⟩	0	0	+1	Data
	MFT 3–4, SFT				+1	+1	Cal
	WFT 1–4, SFT				0	−2	Cal
	WFT 1–4, SFT				−1	+1	Cal
	MFT 3–4, SFT 2–6	WFT 1–4				1	Cal
	WFT 1–4, SFT 3–5	SFT 3–5				−2	Cal
	WFT 1–4, SFT 2–6	SFT 2–6				+1	Cal

重陽子のスピン状態を個別に選択可能

高テンソル偏極を実現可能

構造関数 b_1 測定

$P_{zz} = P_T$
$P_z = P_V$

山形大学
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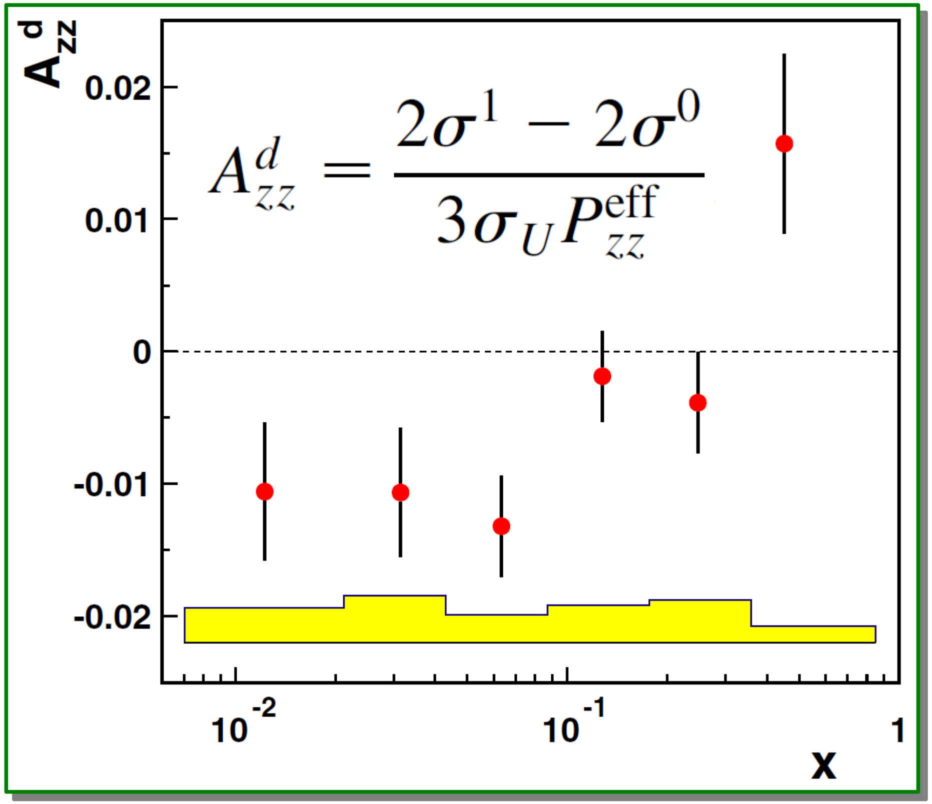
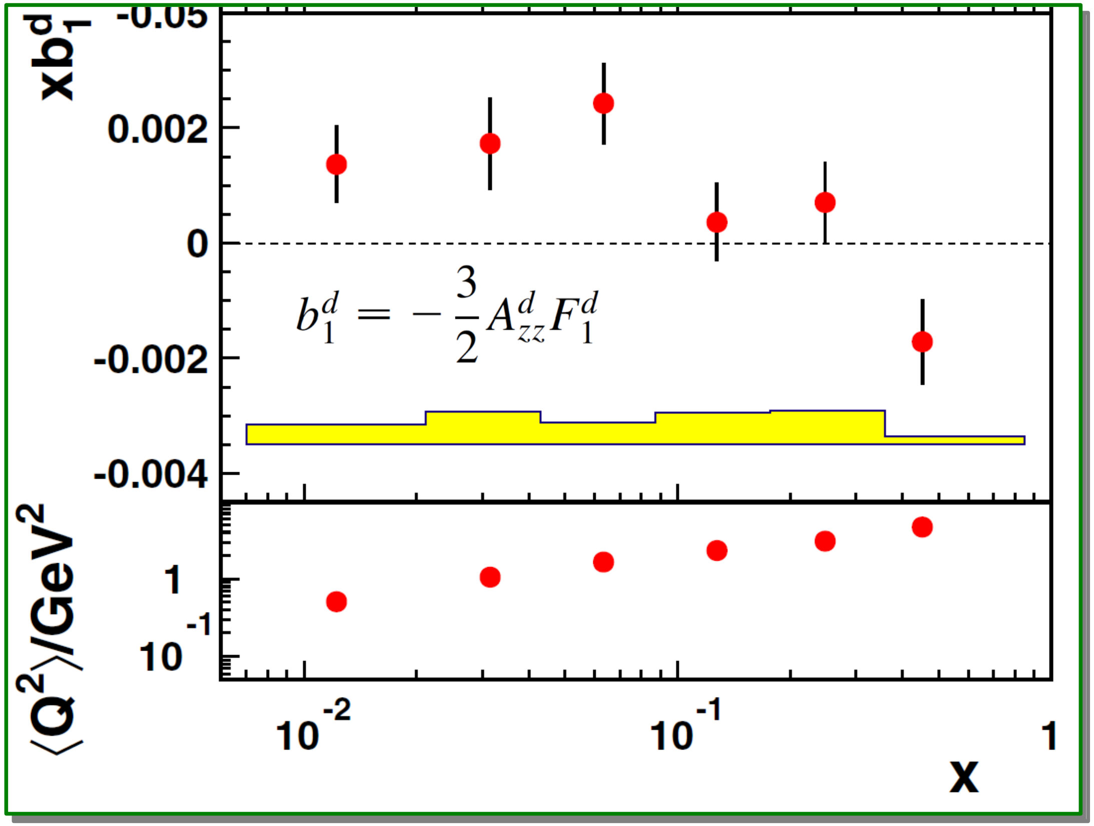
Target state	Hyperfine state	Atomic population	Tensor term P_{zz}	Vector term $P_z \times P_B$	Measured yield
vector$^+$	$\|1\rangle + \|6\rangle$	n^+	$+0.80 \pm 0.03$	$+0.45 \pm 0.02$	$\sigma^{\rightrightarrows}$
vector$^-$	$\|3\rangle + \|4\rangle$	n^-	$+0.85 \pm 0.03$	-0.45 ± 0.02	$\sigma^{\rightleftarrows}$
tensor$^+$	$\|3\rangle + \|6\rangle$	$n^+ + n^-$	$+0.89 \pm 0.03$	0.00 ± 0.01	$\sigma^{\Leftrightarrow}$
tensor$^-$	$\|2\rangle + \|5\rangle$	n^0	-1.65 ± 0.05	0.00 ± 0.01	σ^0



$$A^d_{zz} = \frac{2\sigma^1 - 2\sigma^0}{3\sigma_U P^{\mathrm{eff}}_{zz}}$$



$$b^d_1 = -\frac{3}{2} A^d_{zz} F^d_1$$

固体標的による b_1 測定

※ ILC-N: e-, 250 GeV, ~ 20 nA

偏極DISでの可能性

Beam: e-, 11 GeV (@Hall C), ~100 nA

Target: **Pol. ND$_3$ solid target**

LOI-11-003@JLab

The Deuteron Tensor Structure Function b_1

A Proposal to Jefferson Lab PAC-38
(Update to LOI-11-003)

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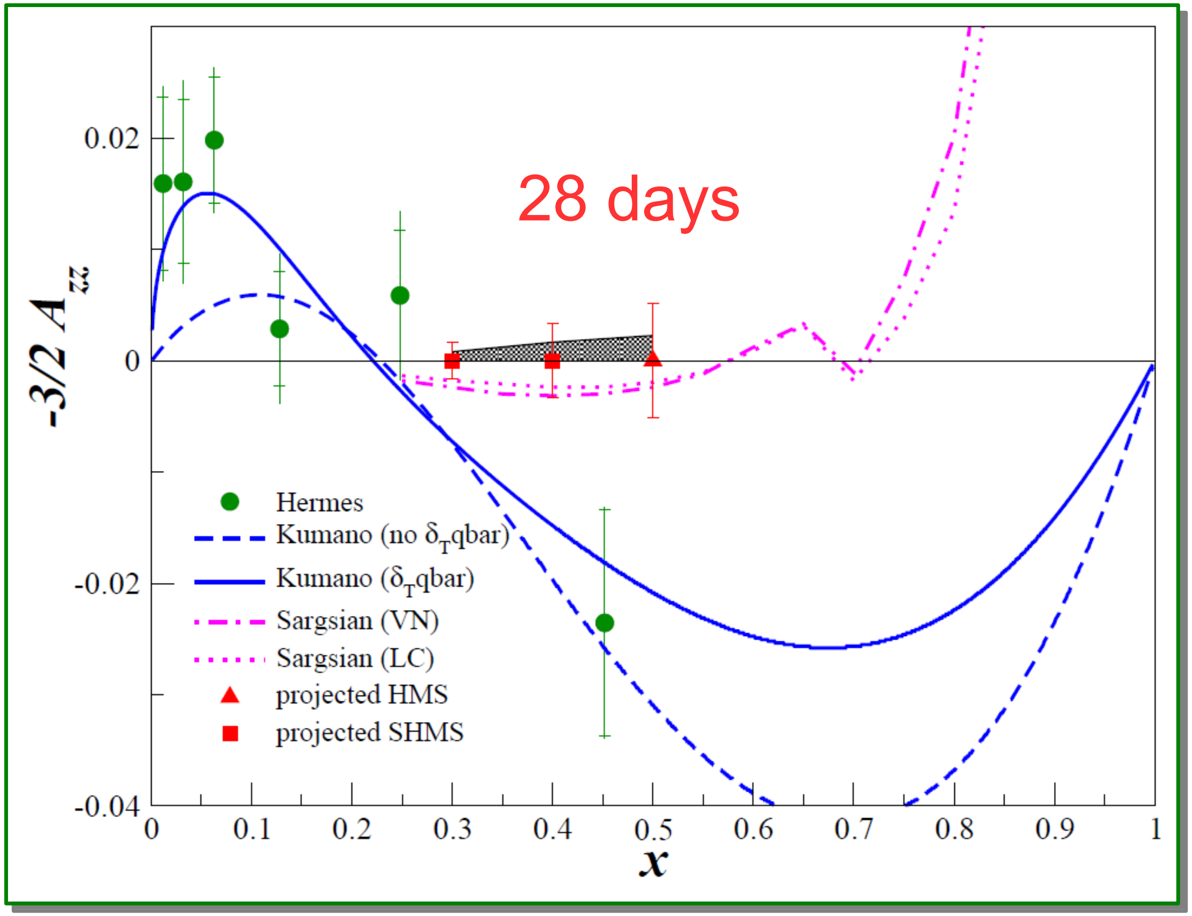
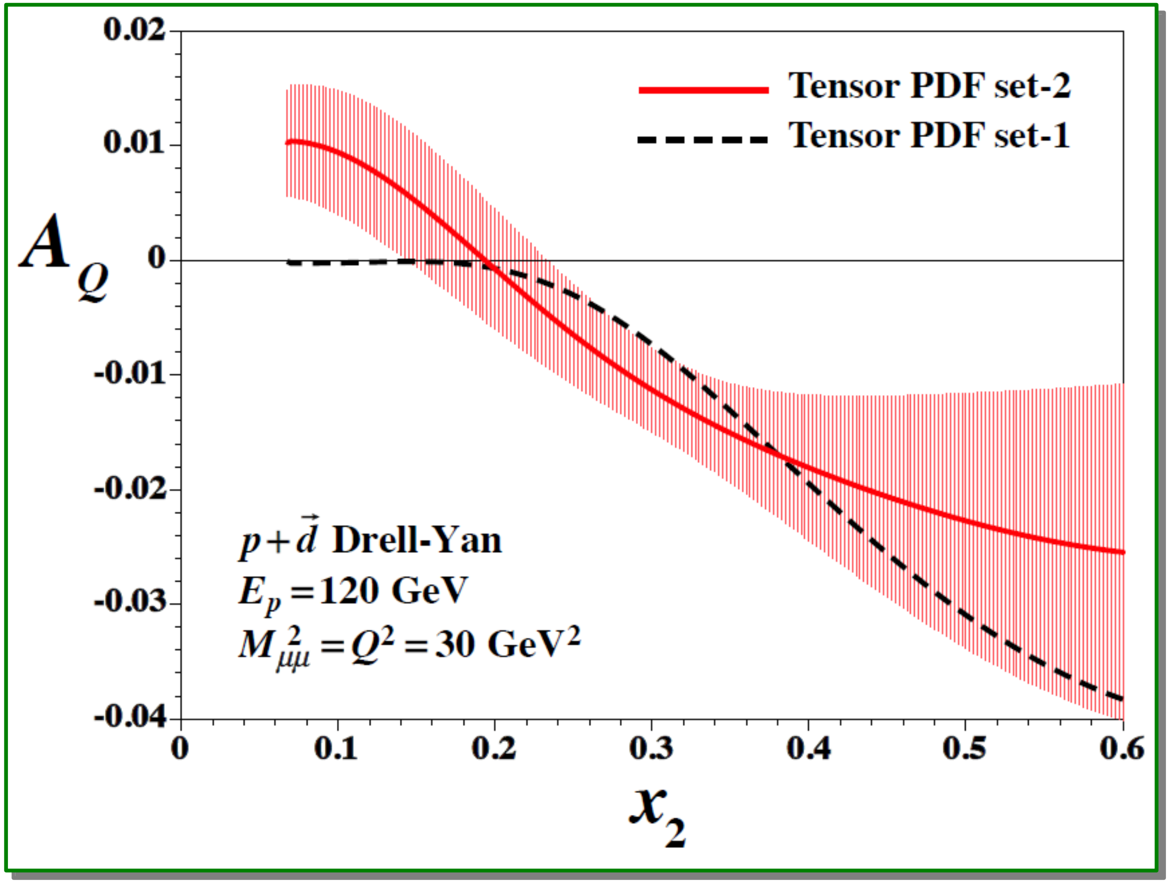


固体標的による b_1 測定

偏極 Drell-Yan での測定

※ Pol(-D) SeaQuest



Shunzo Kumano and Qin-Tao Song,

Phys. Rev. D 94, 054022 (2016)

Target:

Pol. ND_3 solid target?

Polarized Solid Target: ND_3

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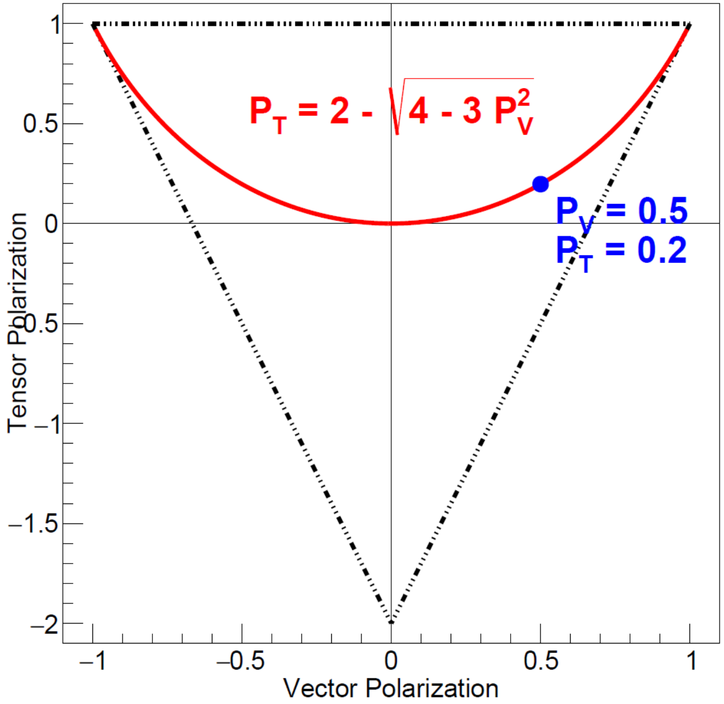
動的核偏極による偏極

- 極低温、高磁場
- 電子偏極 → 重陽子偏極

⇔ **重陽子スピン温度**を電子で冷やす

$$x = \frac{\mu B}{2kT}$$

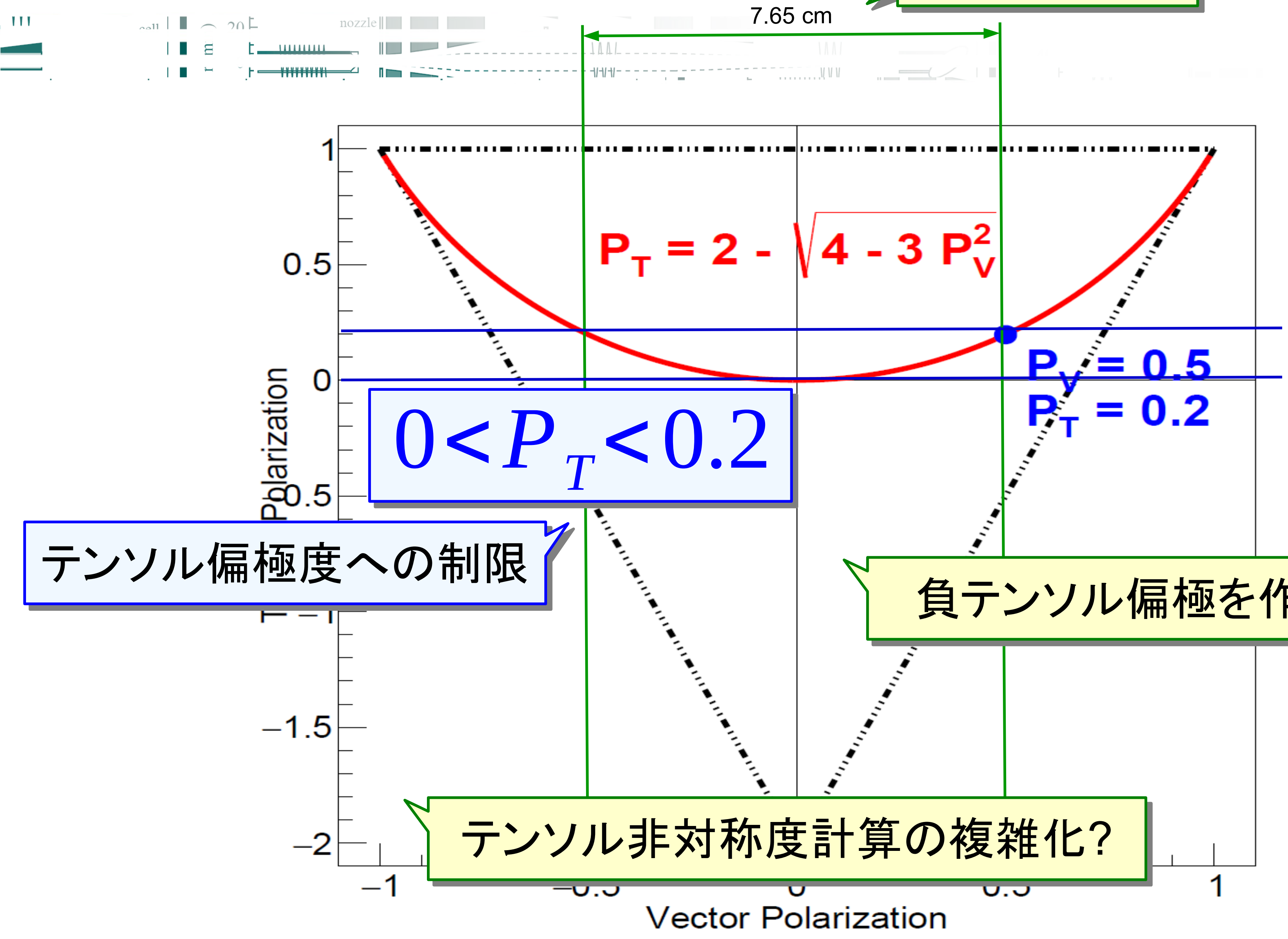


⇒ 高ベクトル偏極度を得る

$$P_V = \frac{4\tanh x}{3 + \tanh^2 x}$$

$$P_T = \frac{4\tanh^2 x}{3 + \tanh^2 x}$$

動的核偏極技術の限界



$|P_V^{\max}| \sim 0.5$

$0 < P_T < 0.2$

テンソル偏極度への制限

負テンソル偏極を作れない

テンソル非対称度計算の複雑化?

Figure of Merit

$$A^d_{zz} = \frac{2\sigma^1 - 2\sigma^0}{3\sigma_U P^{\mathrm{eff}}_{zz}}$$

$$\boxed{P^{\mathrm{eff}}_{zz} = (P^{\overset{\rightarrow}{\Rightarrow}}_{zz} + P^{\overset{\rightarrow}{\Leftarrow}}_{zz} + P^{\Leftrightarrow}_{zz} - 3P^0_{zz})/9}$$

	P_V	P_T	D	f
$\mathrm{ND_3}$	0.4	0.12	0.30	0.036
$^6\mathrm{LiD}$	0.3	0.07	0.50	0.035

※実際は $<|P_T|>$

$$\delta A \propto \frac{1}{P_T \cdot D}$$

HERMESの場合　0.9　~1.0　~0.9
※ガス標的

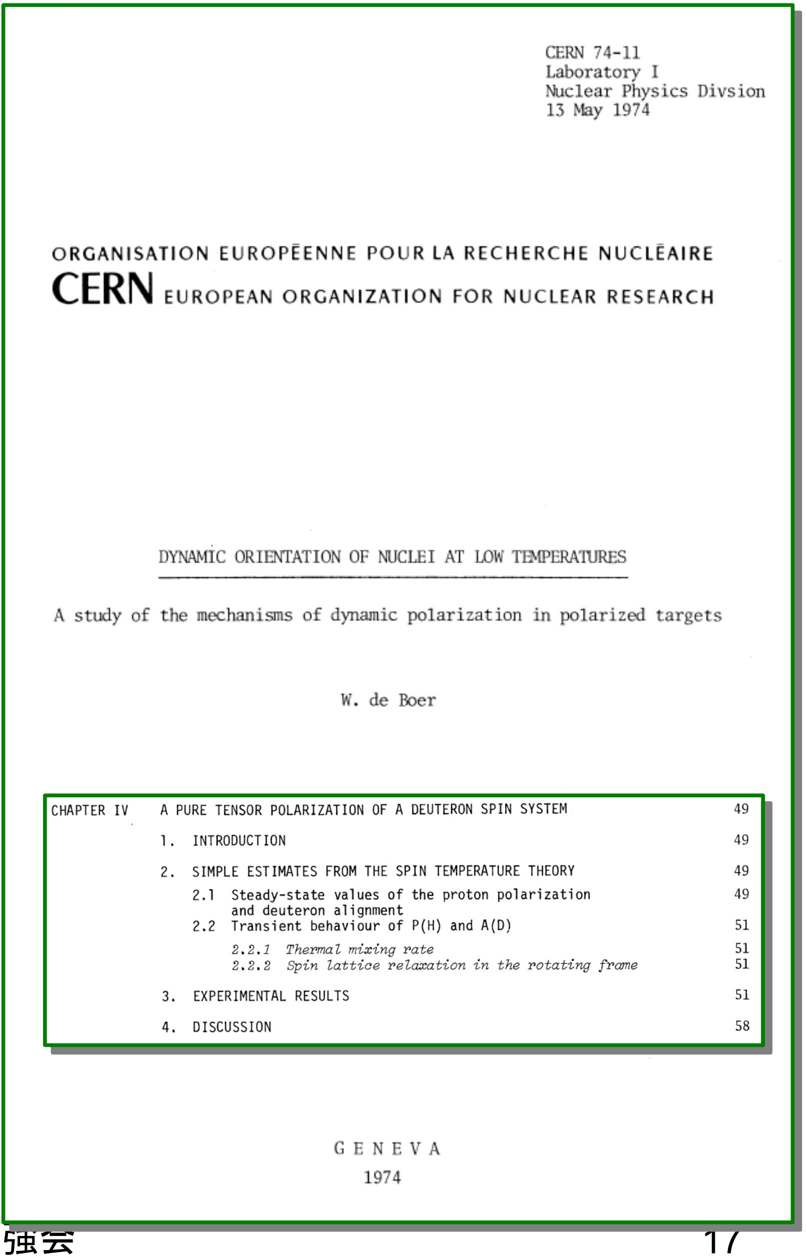
DNPで得られるテンソル偏極度は限界がある $0 < P_T < 0.2$

少しでもテンソル偏極度を増幅できれば効果は大きい?

高ベクトル偏極度を利用できるか?

テンソル偏極化技術

- 核偏極技術における長年の課題
    - ベクトル偏極⇒テンソル偏極
        - RF spin transfer: H⇒D
        - RF hole burning
        - Adiabatic Fast Passage
        - Two microwave tubes
    - 実用的な手法は未確立
    - テンソル偏極度測定の問題



CERN 74-11
Laboratory I
Nuclear Physics Divsion
13 May 1974

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

DYNAMIC ORIENTATION OF NUCLEI AT LOW TEMPERATURES

A study of the mechanisms of dynamic polarization in polarized targets

W. de Boer

GENEVA
1974

詳しくは

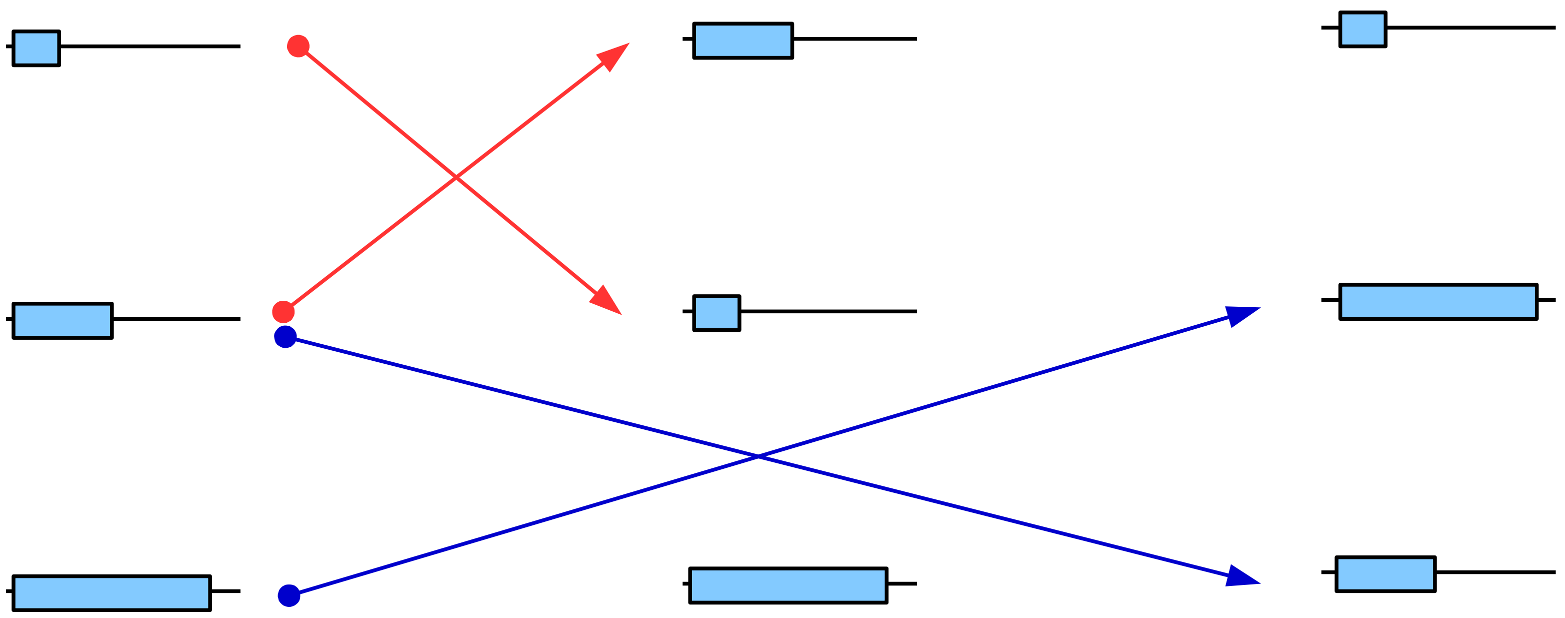
Tensor Polarized Deuterons, Introduction and General Ideas
C. Keith @ Tensor 2014 スライド

テンソル偏極の実現: 基本的な考え方

DNPによる

高ベクトル偏極

高テンソル偏極の実現

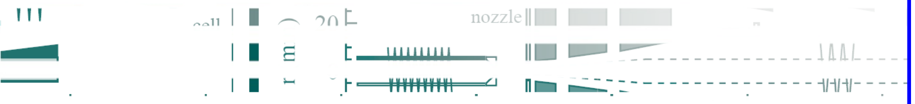


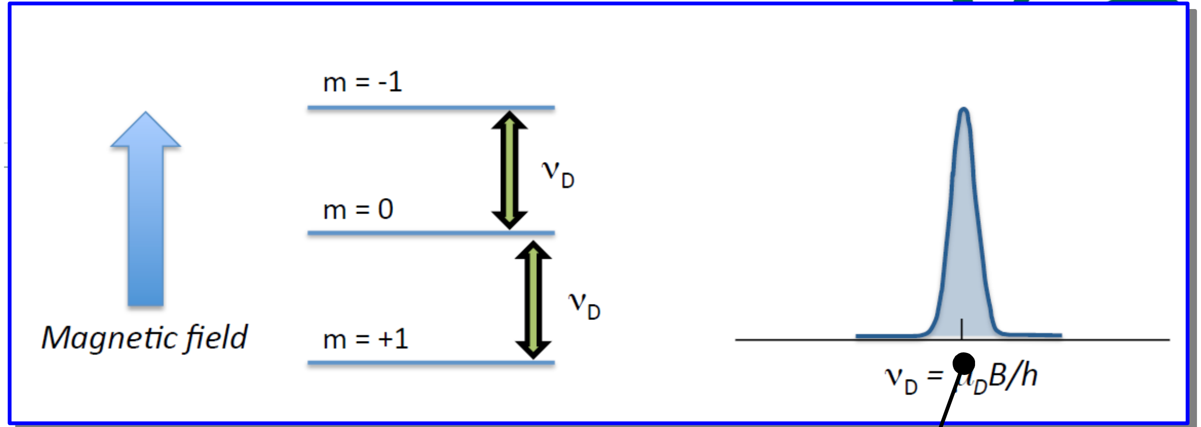
$P_T > 0$

$P_T < 0$

+1⇔0, 0⇔-1 を選別できるのか?

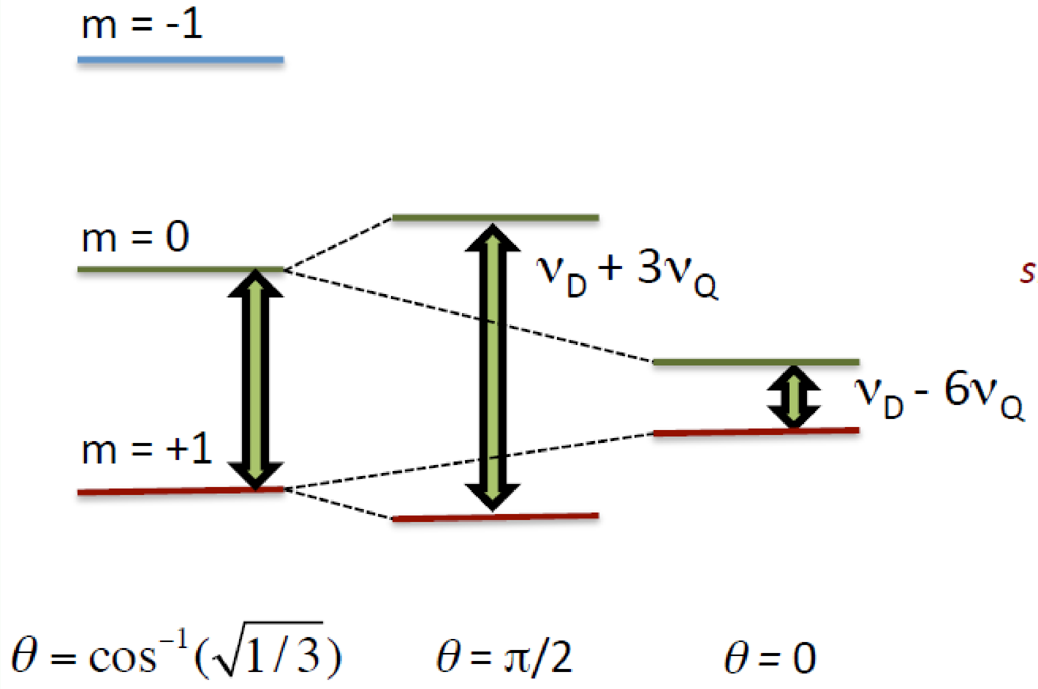
電気四重極モーメントの影響
- NMR信号の形状変化

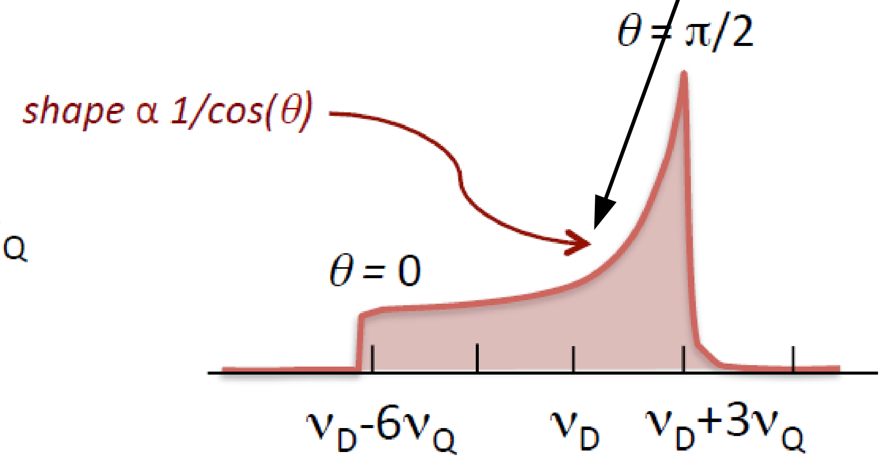




$$E_m = -h\nu_D m + h\nu_Q\left[3\cos^2\theta - 1\right]\left[3m^2 - I(I+1)\right]$$

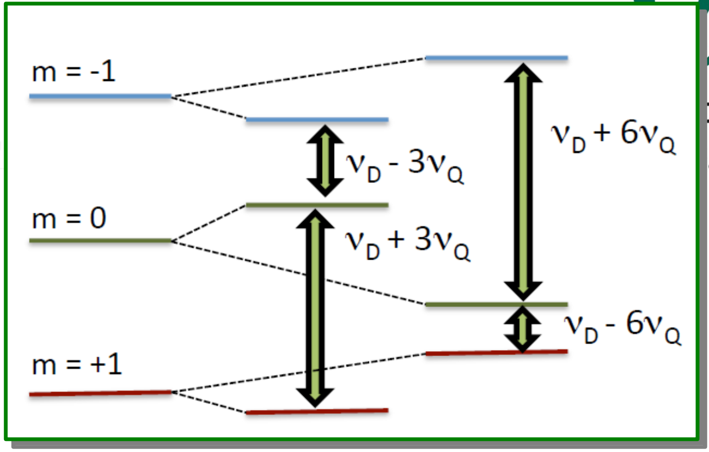
ν_D = deut. Larmor freq. (6.54 MHz/Tesla)
ν_Q = ND_3 quadrupole freq. (335.6 kHz)
= $1/8\ (e^2qQ/h)$
eQ = deuteron quadrupole moment
eq =electric field gradient
θ = angle between eq. & B

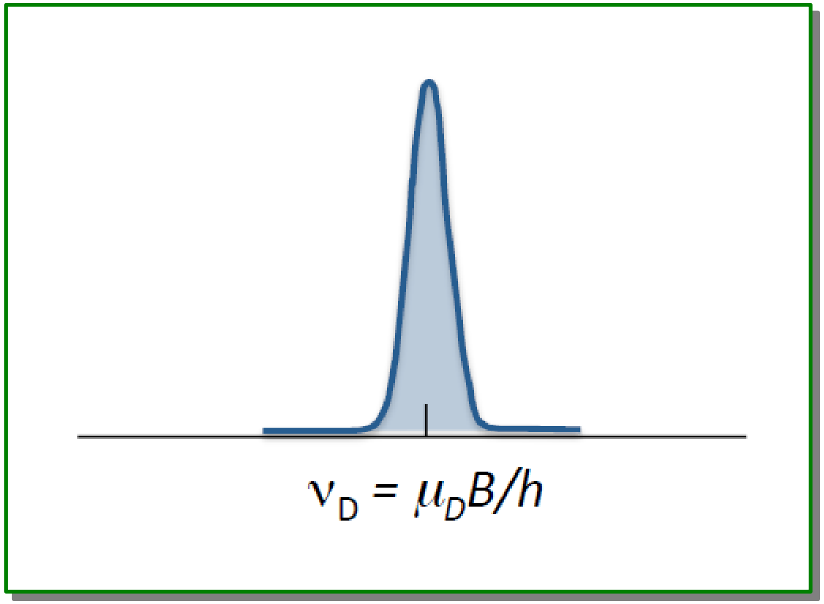




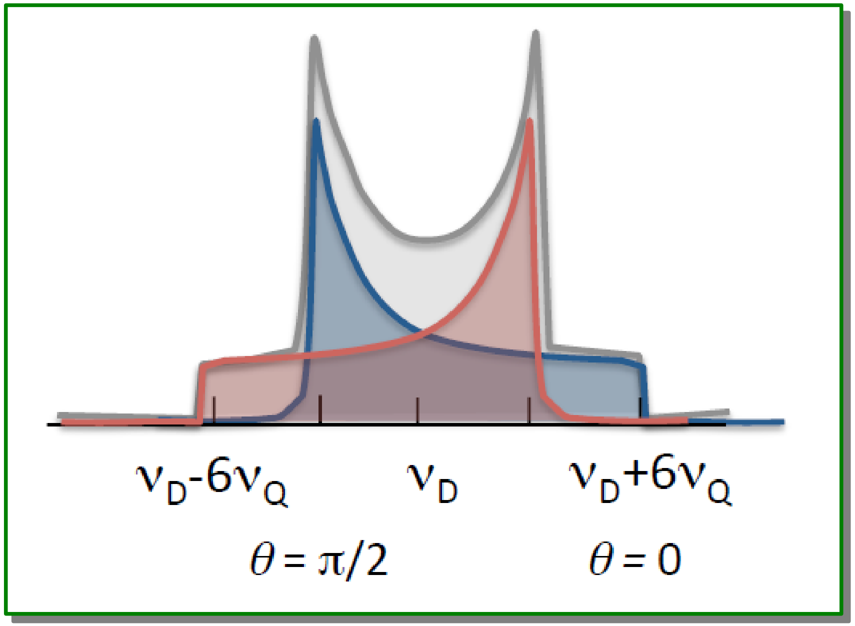
重陽子の NMR信号形

WFT 1–3, SFT 2–4	—	no state	—	—	—	Cat
SFT 3–5	SFT 2–6	|1⟩ |6⟩	0	+1	+1	Data



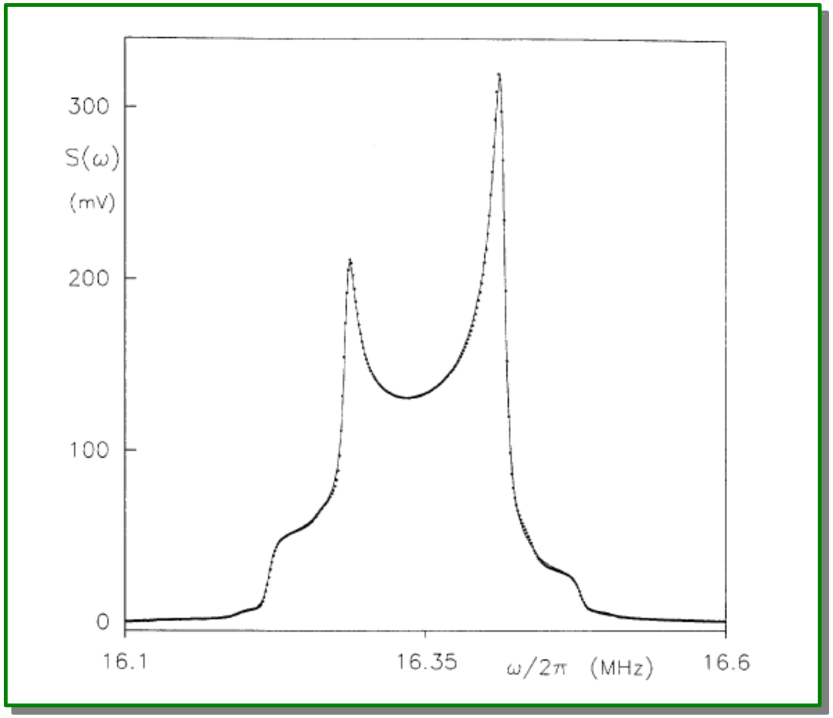


$\nu_D = \mu_D B/h$



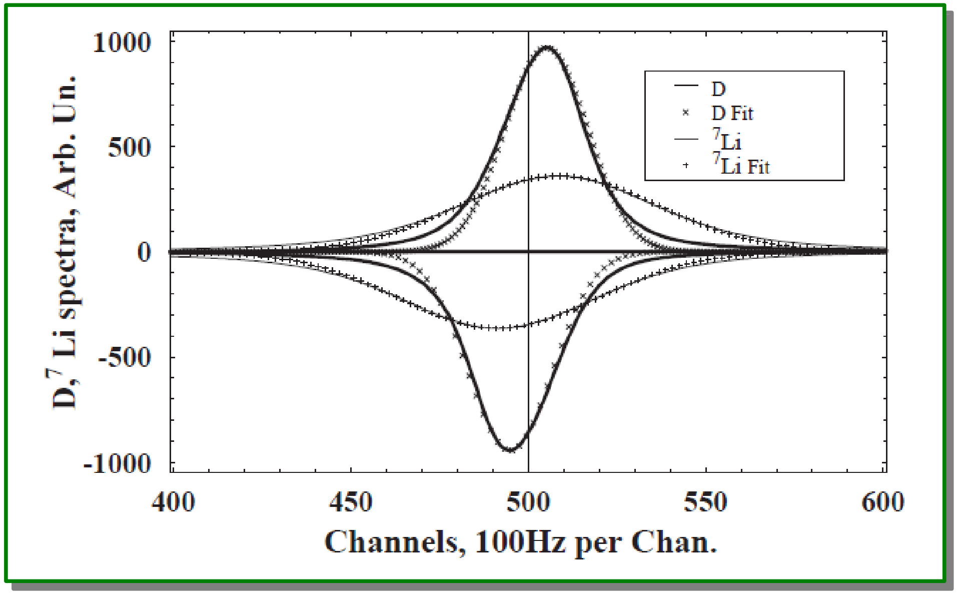
重陽子NMR信号の例

SMC, NIM A398 (1997) 109



ND$_3$, P$_V$=0.44

COMPASS, NIM A526 (2004) 105



^{7}LiD, |P$_V$|~0.4

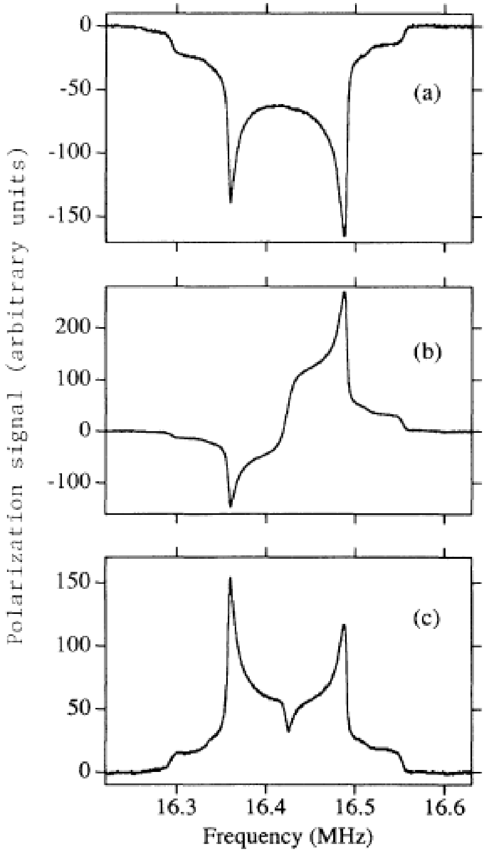
※立方晶系では電気四重極能率が相殺

Adiabatic fast passage: 断熱通過法

WFT 1–3, SFT 2–4	—	no state	—	—	—	Cat
SFT 3–5	SFT 2–6	|1⟩ |6⟩	0	+1	+1	Data

- パルスNMRでの基本的技術
  スピン反転
- 例） DNP後に 0 ⇒ -1 反転
  高テンソル偏極度
- P. Hautle 等による検証
  PRB46(1992)6596
- Frosen Spin Mode
  高強度ビーム実験には不向き

P. Hautle et al, PRB46,6596



a) Polarized d-butanol at 0.5K and 2.5T;

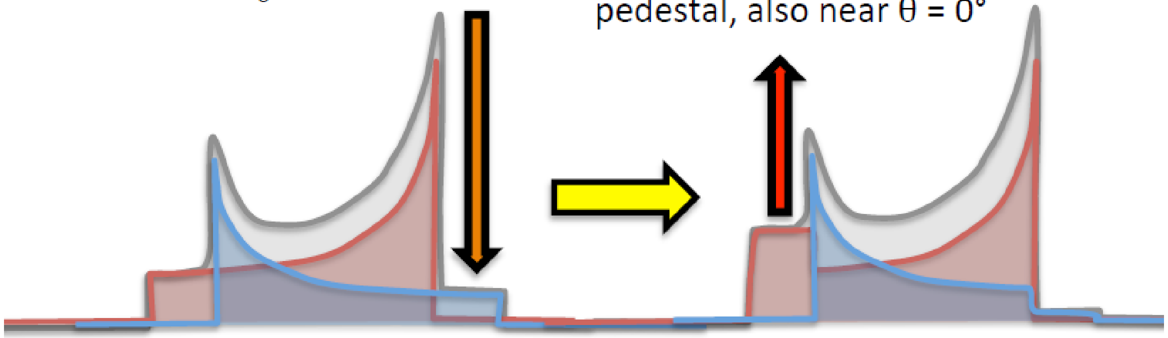
b) After full AFP sweep, low to high frequency

c) After additional half sweep, low to center frequency.

RF hole burning

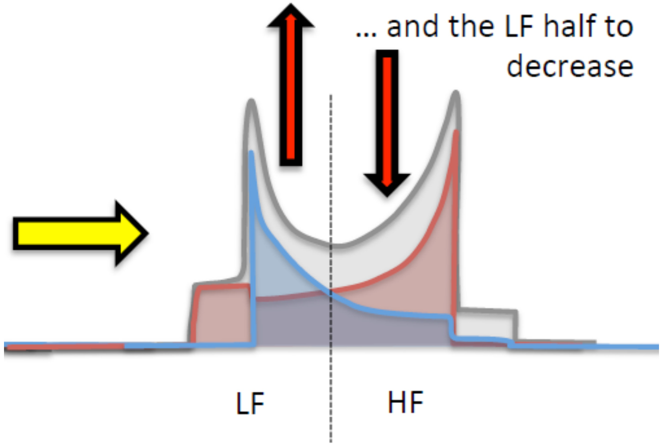
Saturating the HF pedestal reduces N_0 pop. near $\theta = 0°$

This should increase the LF pedestal, also near $\theta = 0°$



Cross relaxation causes the entire LF half to increase…

… and the LF half to decrease



Starting polarization = 37%
RF-induced alignment "up to 20%"

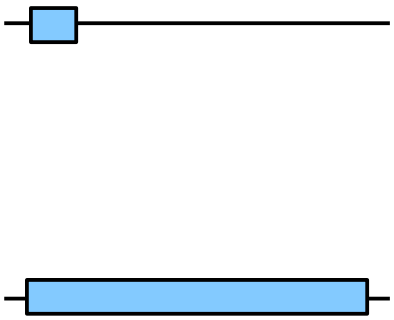
W. Meyer and E. Schiling, Proceedings of 4th Int'l Workshop on Polarized Target Materials and Techniques, Bonn (1984) 165.

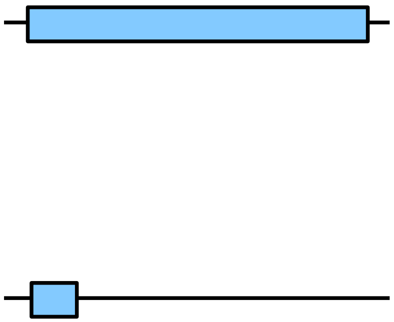
テンソル偏極度測定の技術的課題

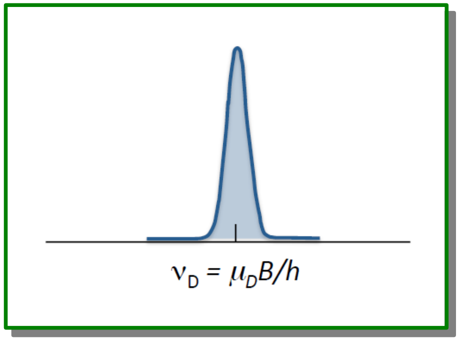
WFT 1–3, SFT 2–4	—	*no state*	—	—	—	Cal
SFT 3–5	SFT 2–6	$\|1\rangle$ $\|6\rangle$	0	+1	+1	Data

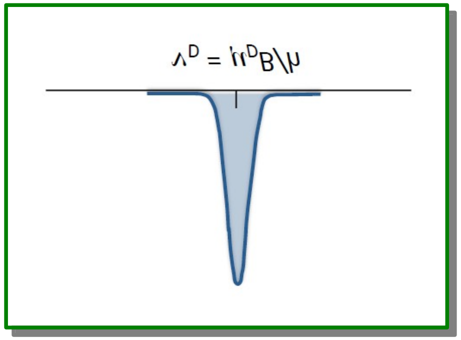
NMR信号強度　＝　ベクトル偏極度

$$P_V \propto S_{NMR}$$

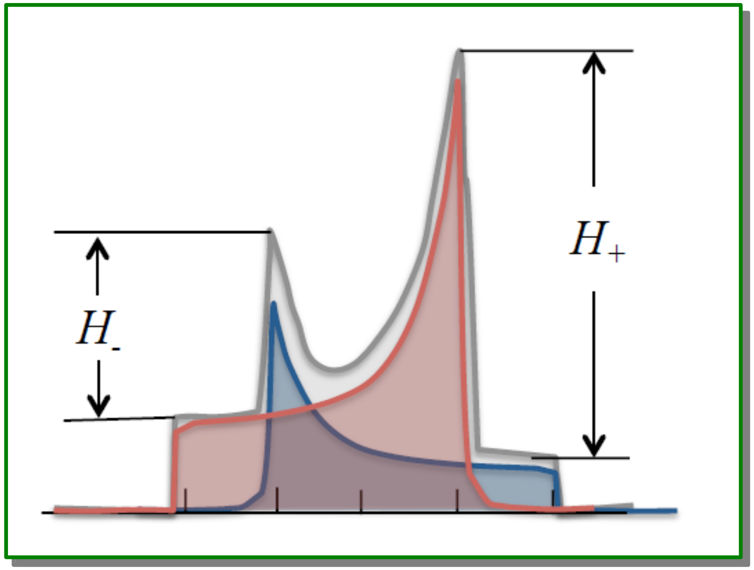








Peak-height method

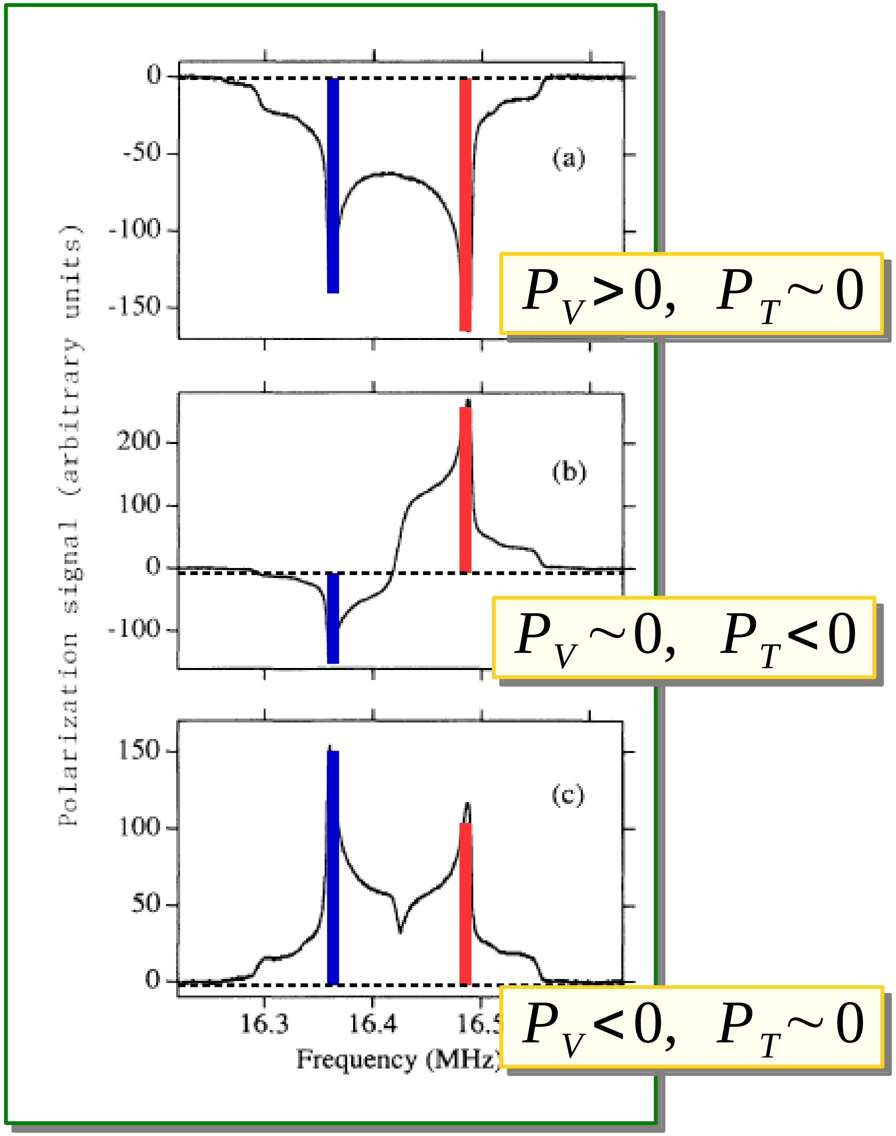


$$P_V = \frac{R^2 - 1}{R^2 + R + 1}$$

$$P_T = \frac{R^2 - 2R + 1}{R^2 + R + 1}$$

$$R = \frac{H_+}{H_-}$$

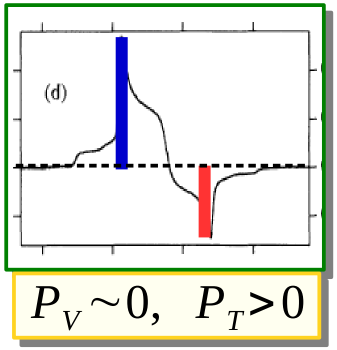
テンソル偏極度測定の技術的課題



$P_V > 0,\ \ P_T \sim 0$

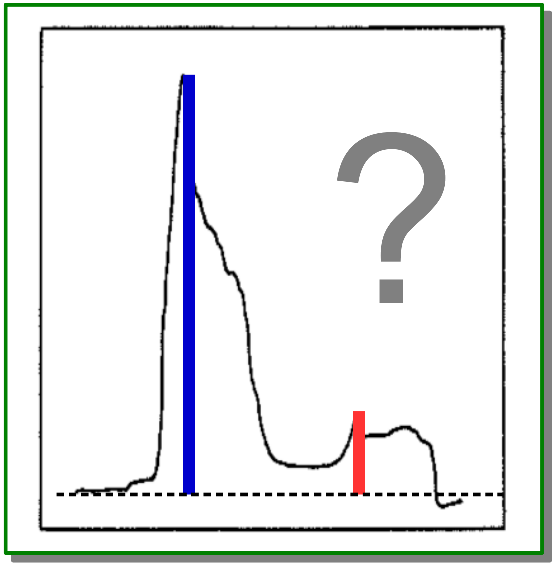
$P_V \sim 0,\ \ P_T < 0$

$P_V < 0,\ \ P_T \sim 0$



$P_V \sim 0,\ \ P_T > 0$

RF-burningでも
適用できるか？



まとめ

- HERMESでの b_1 構造関数測定
  - インターナルガス標的
  - Atomic Beam Source 法
    - スピン状態を選択　⇒　高テンソル偏極
- 固体標的による将来計画（JLab、Fermilab、ILC-N）
  - 動的核偏極（DNP）によるベクトル偏極
  - テンソル偏極への制限
  - 偏極標的技術の課題
    - ベクトル偏極⇒テンソル偏極技術の実現
    - テンソル偏極度測定法の確立