Low-energy Few-Body Experiments

Why do we care about $\vec{p}$olarization ?

Astrid Imig

University of North Carolina /
Triangle Universities Nuclear Laboratory

04/18/2008

overview

- What is few-body physics ?
- Why are we doing it ?
- Why polarization physics ?
- What do we need to measure ?
- What can we learn from the effects in 2, 3, 4N-systems ?

What is few-body physics ?

Oldest Few-Body Problem :
Sun-Earth-Moon

M.Gutzwiller, Rev. Mod. Phys. 70 (1998) 589

1889: Poincaré discovered mathematical chaos

„Few-Body Physics means to calculate observables for a system of few interacting particles exactly or almost exactly“

„→ solve the equations without approximation or as few well controlled approximations as possible.“

Few means the largest number of particles you can treat in this manner

How Many is Few in Few-Nucleon Physics ?

Discrete states (bound and excited states)

A = 2,3 → exactly on PC

A = 4 → exactly on supercomputer

A = 5,6, …, 8 (9,10) → on supercomputer with GFMC

Continuum states (scattering observables)

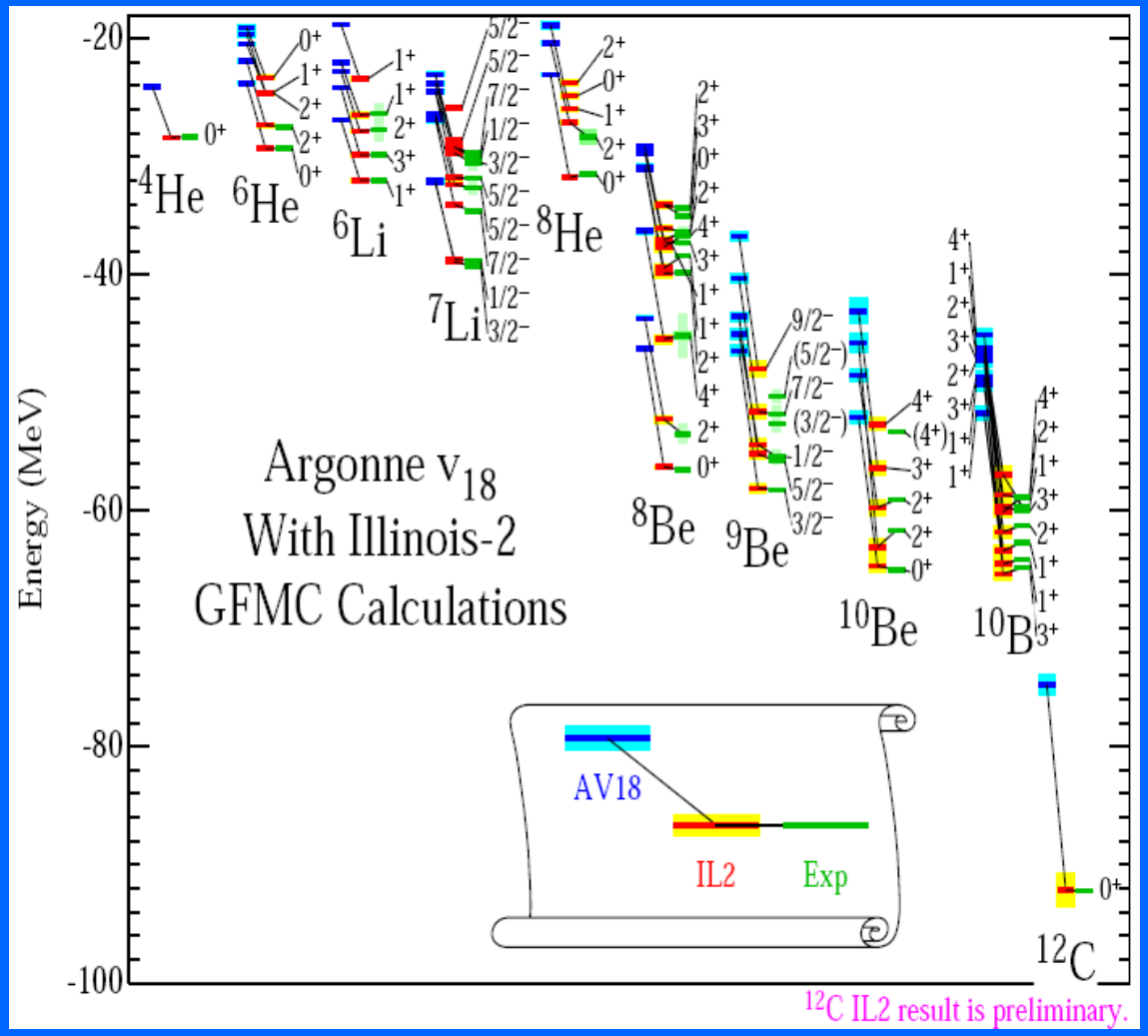
A = 2 → exactly on PC

A = 3 → exactly on supercomputer

A = 4 → approximately on supercomputer

> 4N-system

A = 10 : 10000 processor hours for one state



S. Pieper et al.,
Nucl. Phys. A 751 (2005) 516

Why are we investigating this?

Two Nucleon System

Wealth of
NN scattering data

Two Nucleon Force

1935 Yukawa's
Meson Theory

1990's

Realistic Modern NN Forces
CD-Bonn, AV18, Nijmegen I,II,93
reproduce 3500 exp. NN data
with high precision, $\chi^2 \sim 1$

Three Nucleon System

1960 Faddeev Theory
Exact Solution of 3N-System
with NN forces

Three Nucleon Force

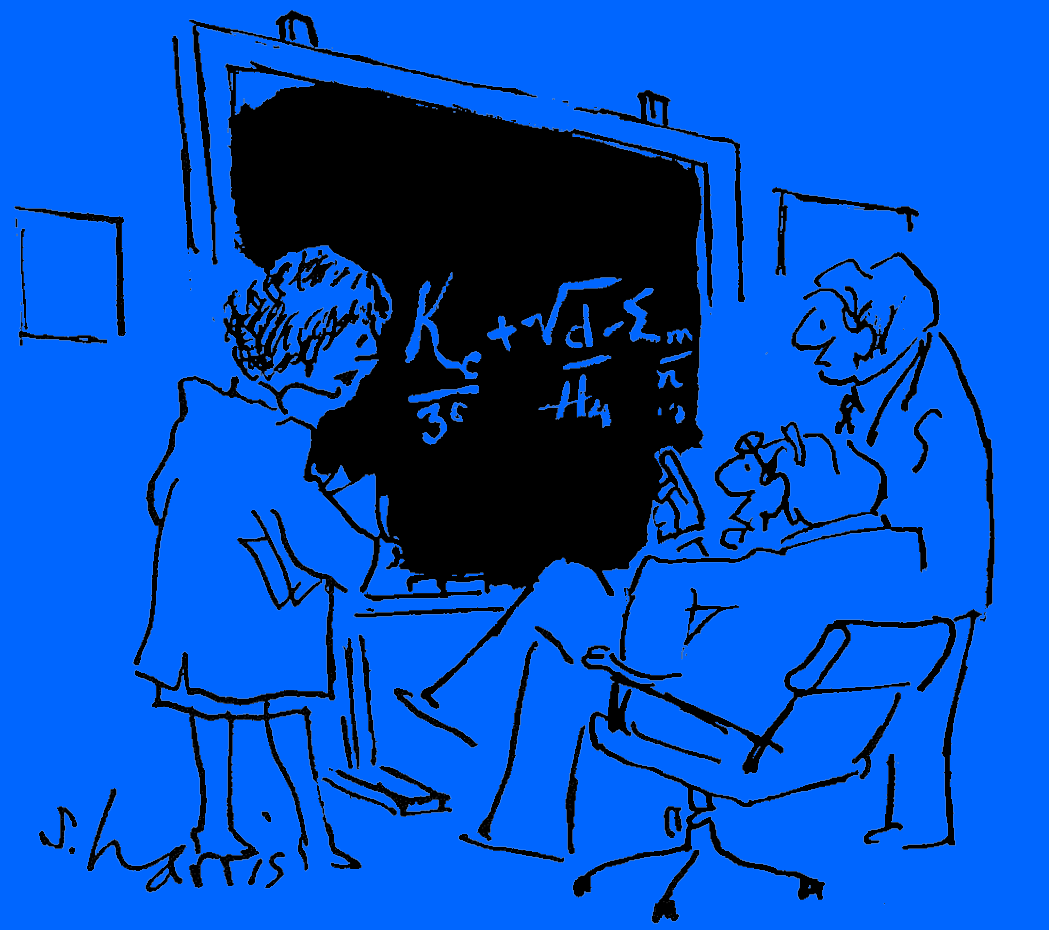
Why are we investigating this?

3N system largest to be solved exactly

Smallest system where to learn about 3NFs

Potential-Modelle	^{3}H-Bindungsenergie (MeV)	
CD-Bonn	8,00	2NF
Argonne-18	7,62	2NF
Nijmegen II	7,62	2NF
CD-Bonn + TM	8,48	3NF
Argonne-18 + TM	8,48	3NF
Argonne-18 + TM99	8,45	3NF
Argonne-18 + Urb-IX	8,48	3NF
Experiment	8,48	

Why polarization physics …



"LET'S SEE IF WE COULD PUT A SPIN ON IT AND GET THE PUBLIC INTERESTED."

… somewhat special,

but very instructive !

… many observables

Zero-Spin observable σ

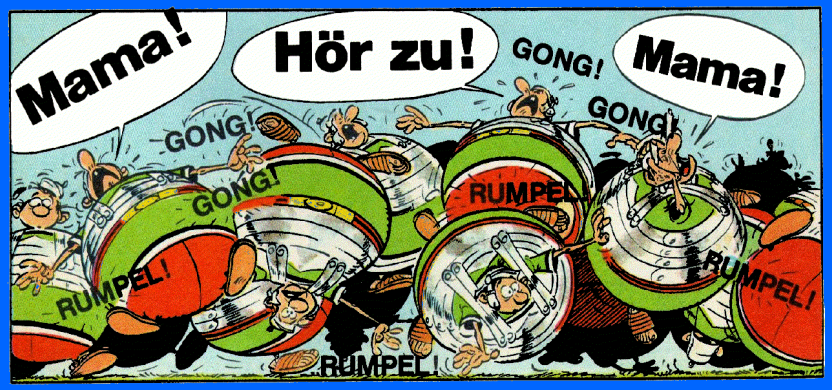
Spin 1 – Spin ½ transfer :

One-Spin observables A_y, A_{xz}, A_{zz}, A_{xx-yy}

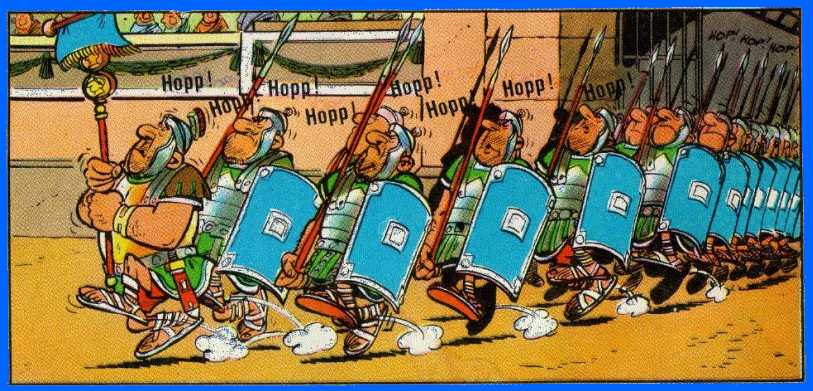
Two-Spin observables $K_y^{y'}$, $K_x^{x'}$, $K_z^{x'}$, $K_z^{z'}$, $K_x^{z'}$

$K_{xy}^{x'}$, $K_{yz}^{x'}$, $K_{xz}^{y'}$, $K_{xx-yy}^{y'}$, $K_{zz}^{y'}$, $K_{xy}^{z'}$, $K_{yz}^{z'}$

Even the old Romans knew …

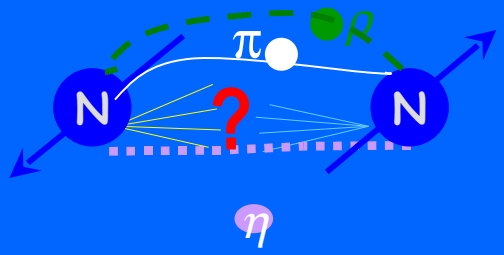


unpolarized



polarized

Considerably more information about nuclear forces

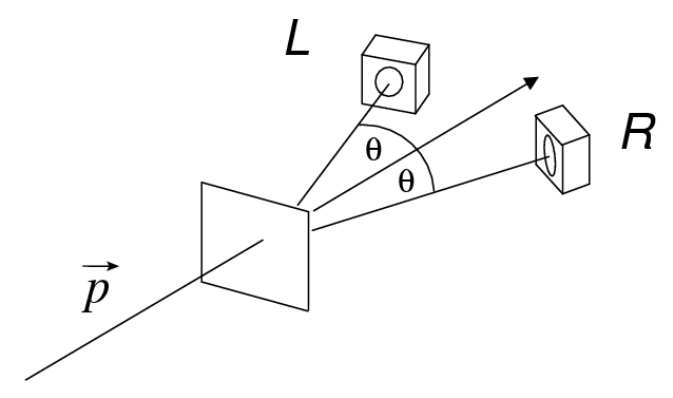


Spin ½ : Polarization determination

Setup with Two-Detector-System:

$$L = n \cdot N_A \cdot \Delta\Omega_L \cdot E \cdot \left(\frac{d\sigma}{d\Omega}\right)_0 \cdot (1 + p_y A_y)$$

$$R = n \cdot N_A \cdot \Delta\Omega_R \cdot E \cdot \left(\frac{d\sigma}{d\Omega}\right)_0 \cdot (1 - p_y A_y)$$



Polarization states: $\uparrow, \downarrow, *$

Left-Right-Asymmetry: $\varepsilon = \sqrt{\frac{L^{\uparrow} \cdot R^{\downarrow}}{L^{\downarrow} \cdot R^{\uparrow}}}$

➥ Vector polarization: $p_y = \frac{2}{3} \cdot \frac{1}{A_y} \cdot \frac{\varepsilon - 1}{\varepsilon + 1}$

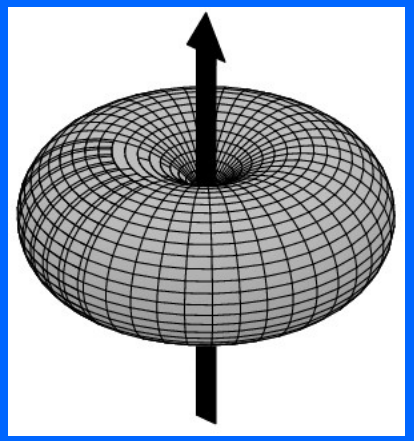
Deuterons:

Spin 1 : Polarization determination

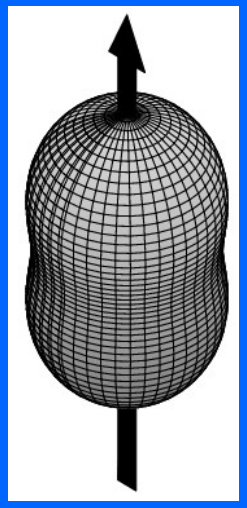
Setup with 5-Detector-System

Polarization states: N_0, N_+, N_-

With $N_0 + N_+ + N_- = 1$



$N_0=1$, $N_+=N_-=0$



$N_+=1$,
$N_0=N_-=0$

Vector polarization:

$$p_z = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$$

Tensor polarization:

$$p_{zz} = \frac{N_+ + N_- - 2N_0}{N_+ + N_0 + N_-}$$

Polarization

Essential for polarization experiments:

- Polarized beams
- Polarimeters to determine the polarization

Beams are polarized by nuclear reaction
or
Polarized ion sources

W. Haeberli, Ann. Rev. Nucl. Sci. 17 (1967) 373

Cologne:

- Lambshift Source

V. Bechtold, NIM 150 (1978) 407

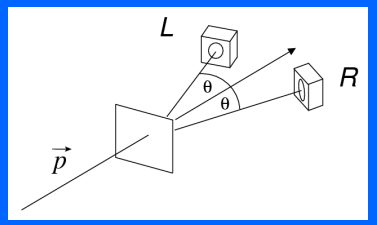
Polarization

- Beam polarimeters

  $^{3}He(d,p)^{4}He$

  $^{4}He(p,p)^{4}He$

  $^{4}He(d,d)^{4}He$



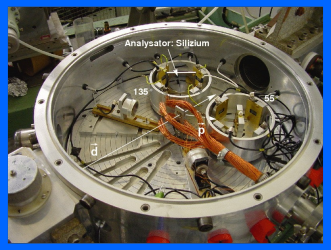
- Transfer polarimeters

  $^{4}He(p,p)^{4}He$

  $^{12}C(p,p)^{12}C$

  $^{28}Si(p,p)^{28}Si$

  $^{3}He(d,p)^{4}He$

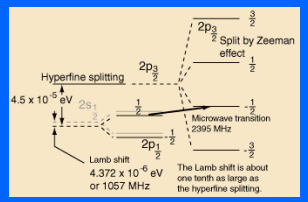


L. Sydow et al., Nucl. Phys. A567 (1994) 55

A.I. et al., Phys. Rev. C 73 (2006) 024001

L. Sydow, S. Vohl et al., Few-Body Systems 25 (1998) 133

- Lambshift polarimeter



R. Engels et al.,
Rev. Sci. Instr. 74 (2003) 4607

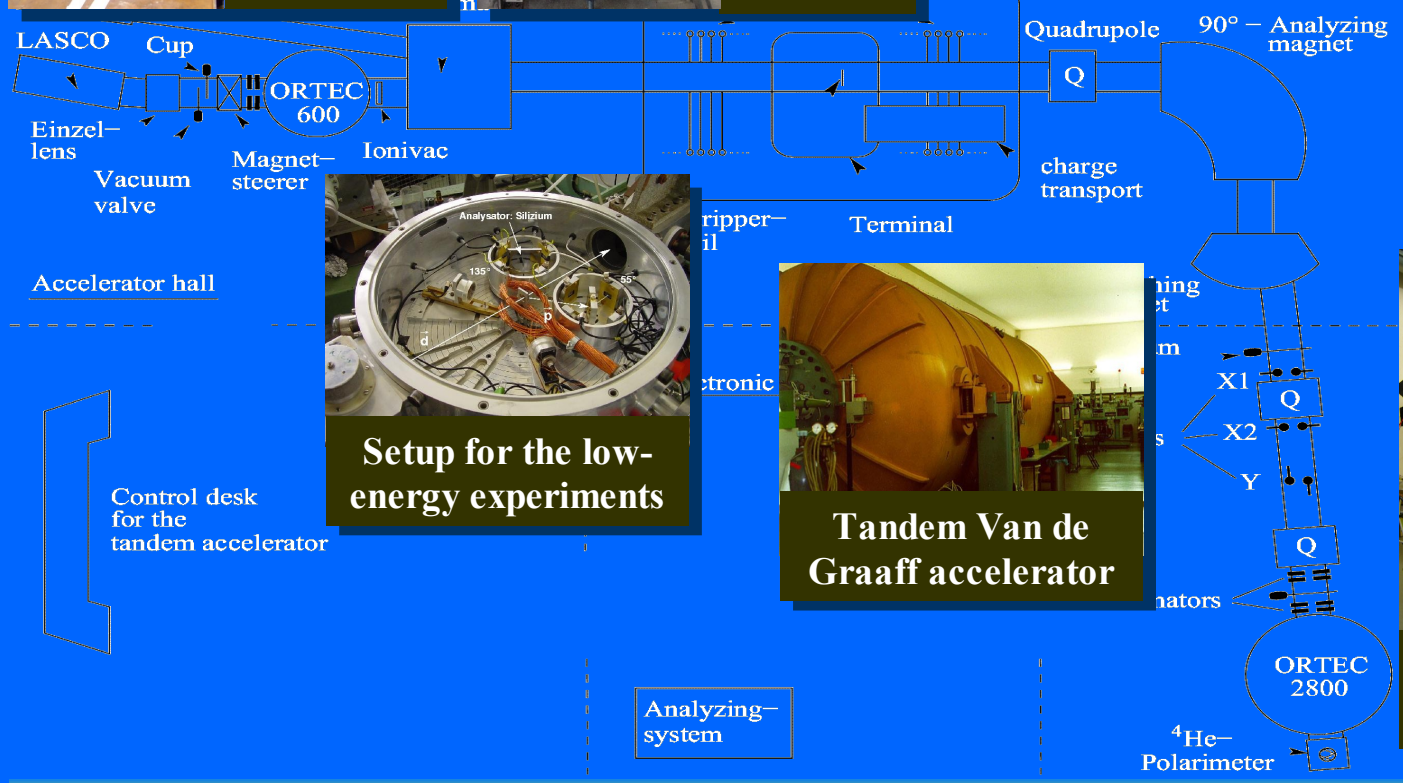
Cologne FN tandem accelerator facility: scattering setups

Polarized Ion Source LASCO
p **+ vector & tensor *d***

E* ×*B

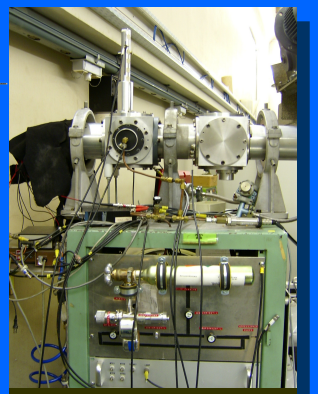
Spin Rotator

Beam polarizations:
≈ 70-75% of theo. values

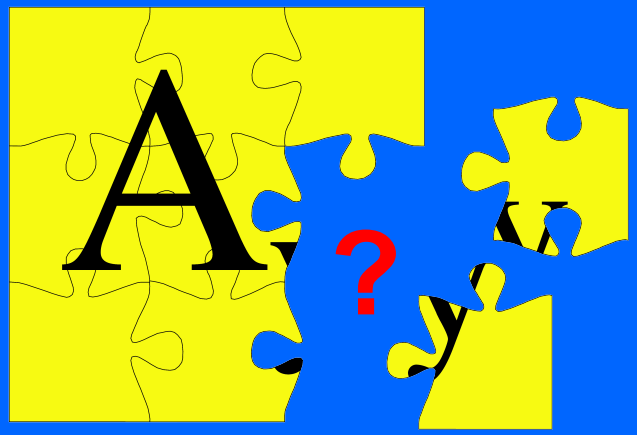


Setup for the low-energy experiments

Tandem Van de Graaff accelerator



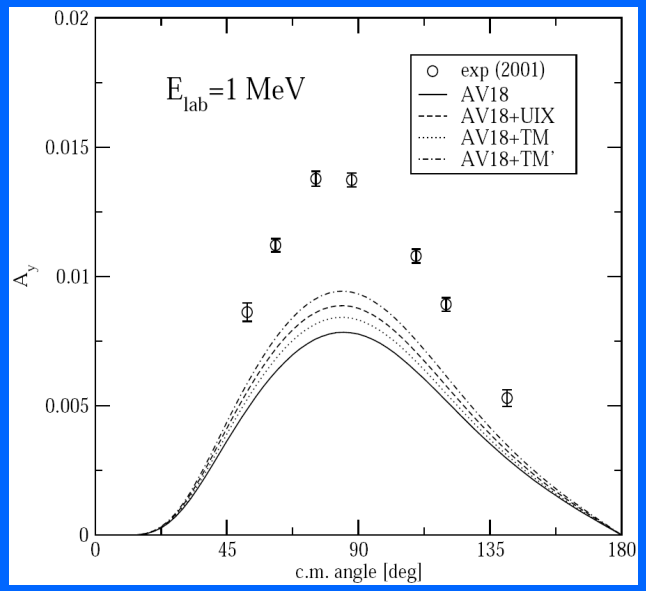
Beam Line Polarimeters



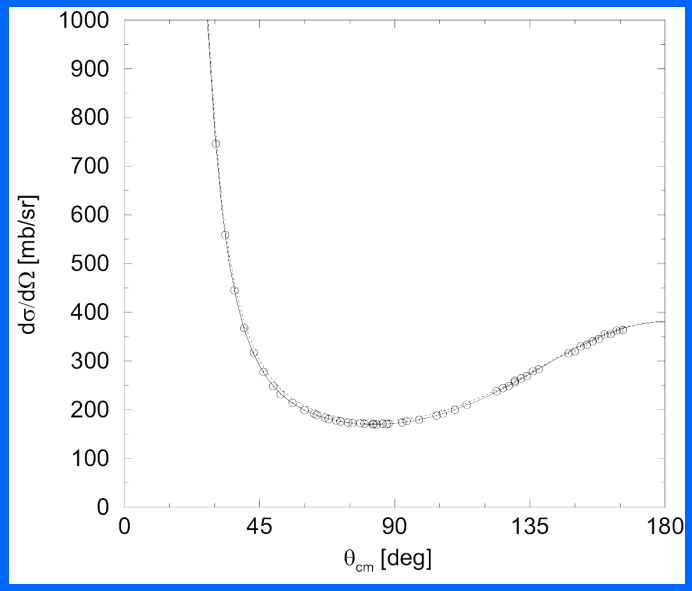
@ low energies :

elastic *pd* scattering

H. Arenhövel et al., nucl-th/0412039

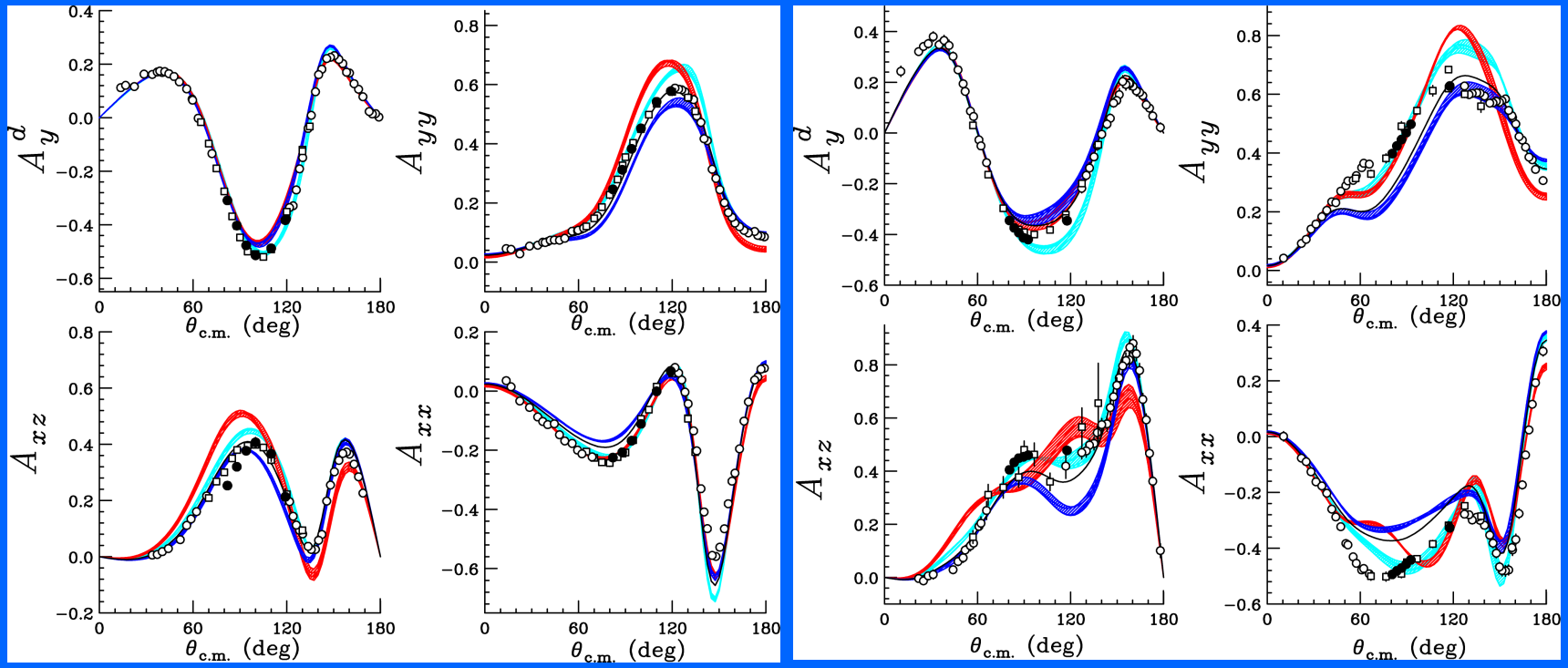


A. Kievsky et al., Phys. Rev. C 63 (2001) 024005



@ RIKEN

$d-p$ at 70MeV/nucleon **$d-p$ at 135 MeV/nucleon**



NN Forces Only

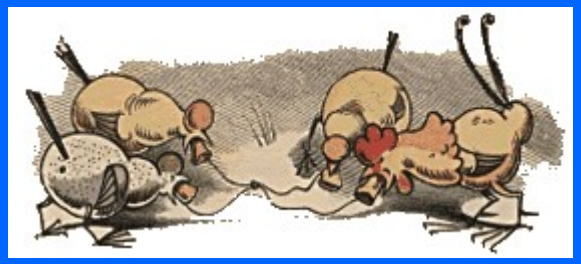
NN + Tucson Melbourne (TM) 3NF

NN + TM'(99) 3NF – closer to chiral symmetry

K. Sekiguchi et al., PRC 65 (2002) 034003
K. Sekiguchi et al., PRC 70 (2004) 014001

4N-system

Many experimental challenges in determination of PTCs but also theoretically…

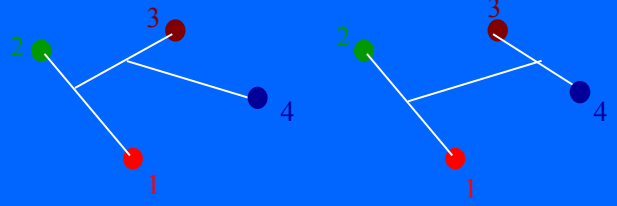


„Max und Moritz“ by W. Busch

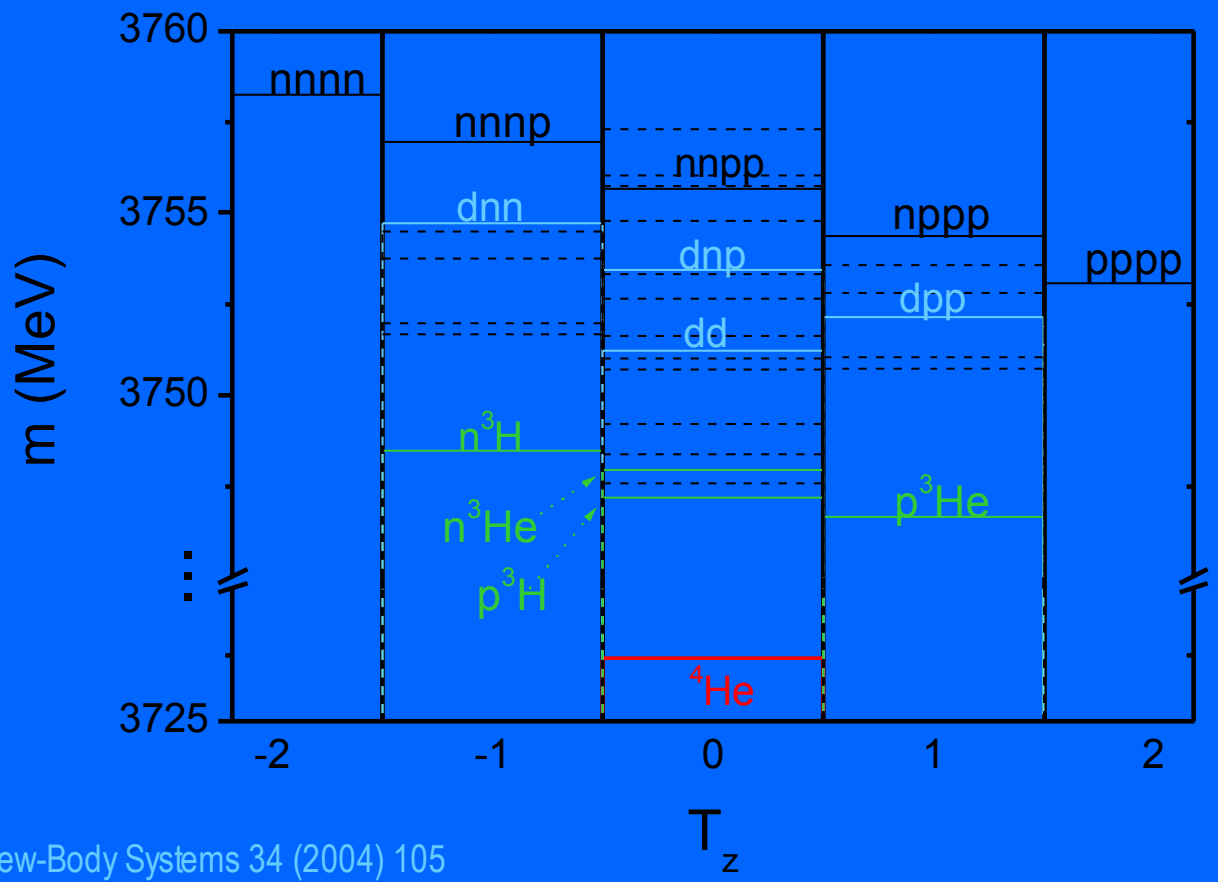
A = 4 system as laboratory

Test other dynamical aspects of NN potentials than A = 2, 3

New, yet not solved, problems



Complexity of the 4N-system



R. Lazauskas, Few-Body Systems 34 (2004) 105

D+D fusion

Few-Body reactions of astrophysical relevance:

$p + p \rightarrow d + e^+ + \nu_e$

$p + {}^3He \rightarrow {}^4He + e^+ + \nu_e$

${}^2H(p,\gamma){}^3He$

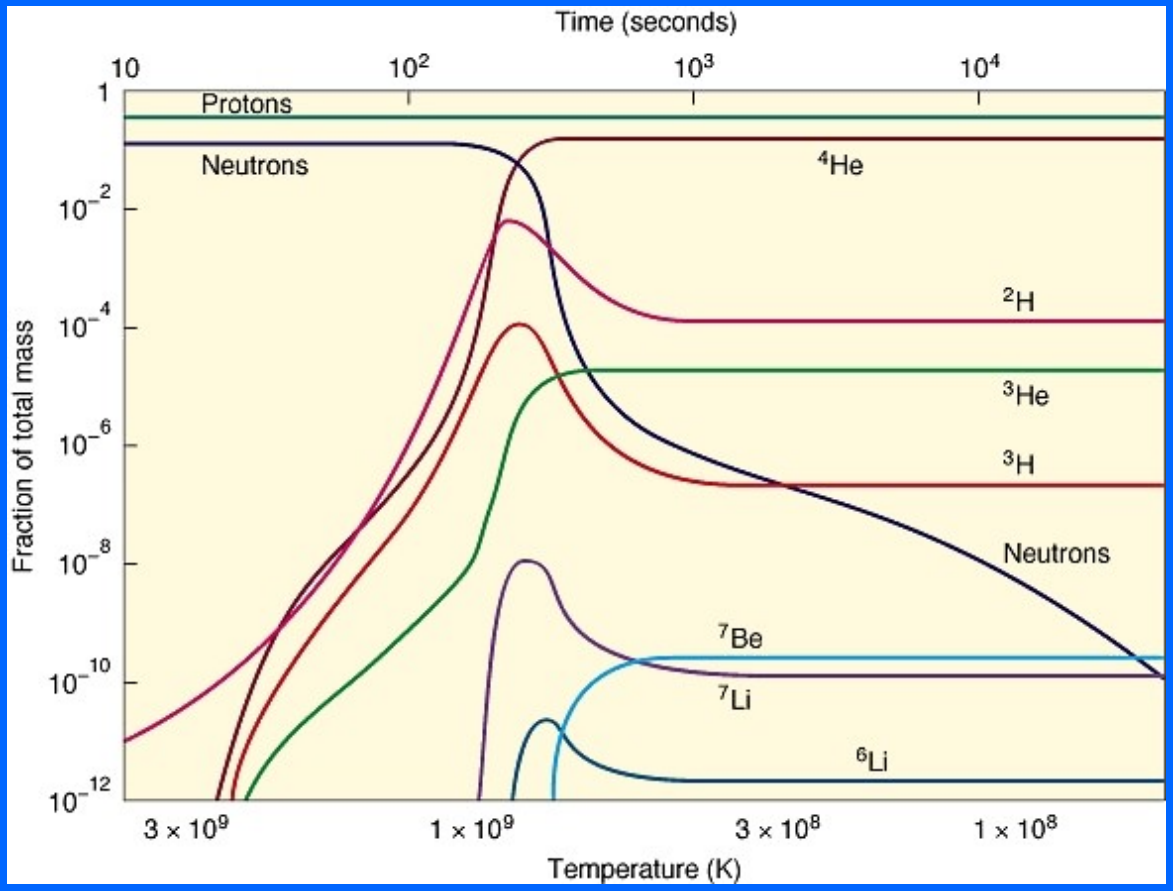
Especially:

$$d + D \rightarrow p + {}^3H$$

$$d + D \rightarrow n + {}^3He$$

Big Bang-Nucleosynthesis

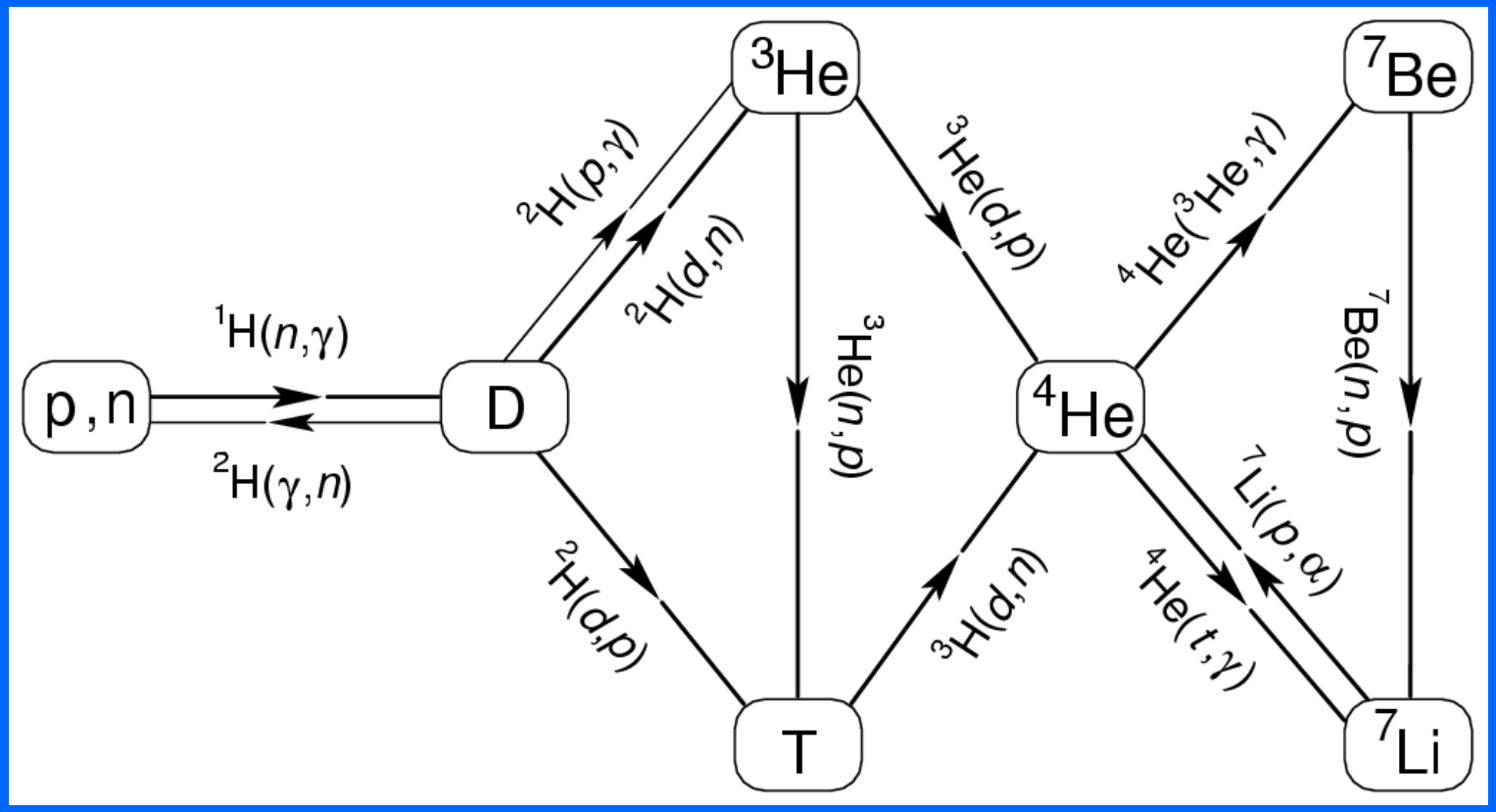
Deuterium is
„cosmic baryometer“



Astrophys. J. 148 (1967) 3

Big Bang - Nucleosynthesis

primordial key reactions

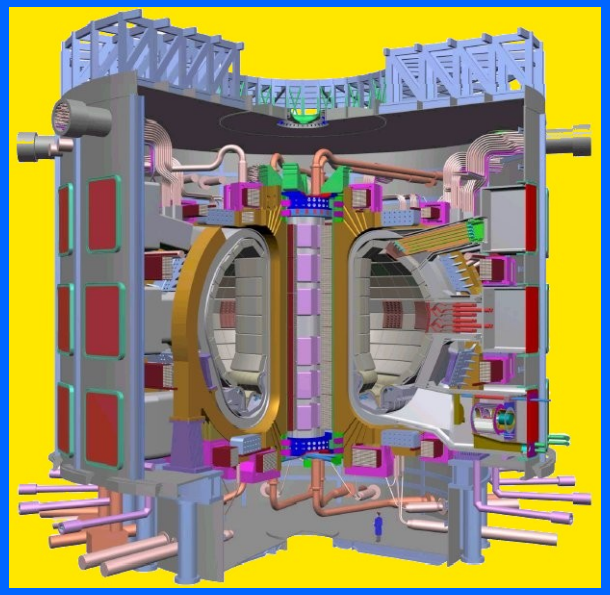


D+D fusion

$d + T \rightarrow n + {}^4He$ Q = 17.58 MeV

$d + {}^3He \rightarrow p + {}^4He$ Q = 18.35 MeV

Fusion reactor ITER, France

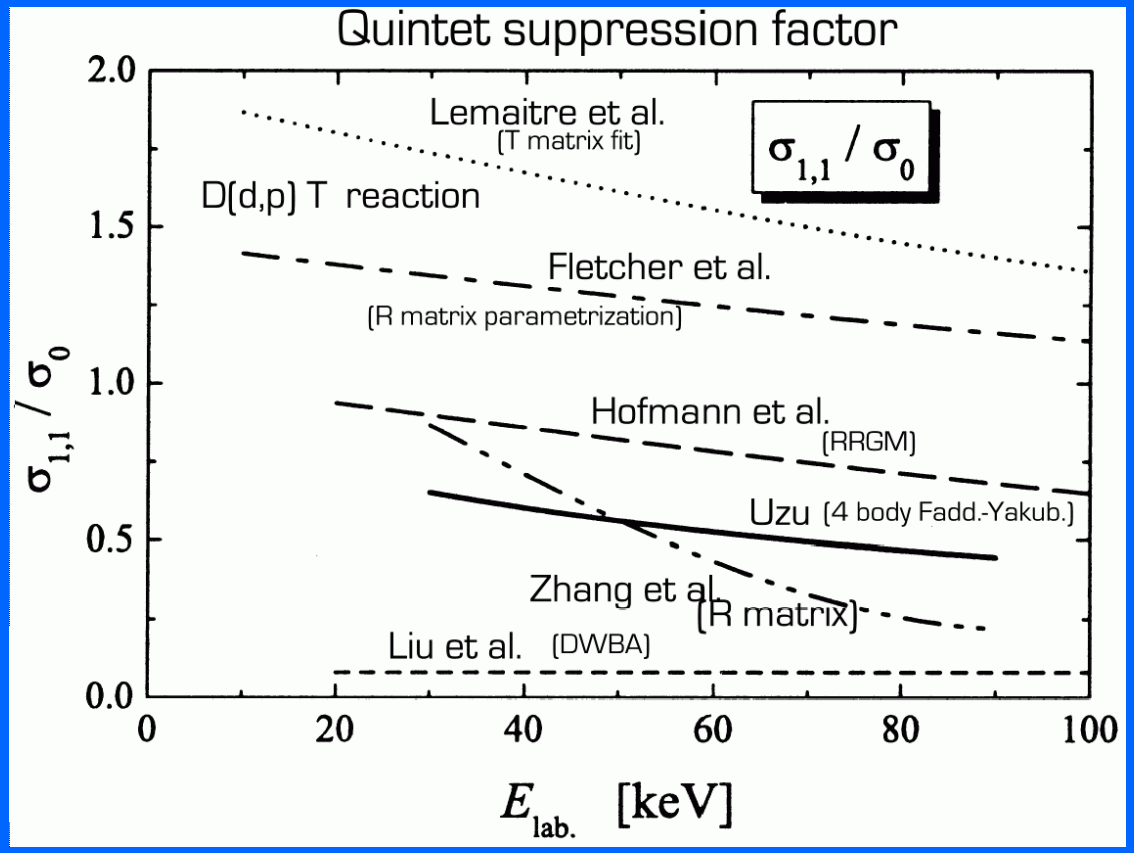


but : $d + D \rightarrow n + {}^3He$

with polarized particles:

- increase of the reaction rate
- decrease of the neutron production
  - ↳ reduction of costs

D+D fusion



H. Paetz gen. Schieck et al., Phys. Lett. B 276 (1992) 290

S. Lemaître et al., Ann. Physik 2 (1993) 503

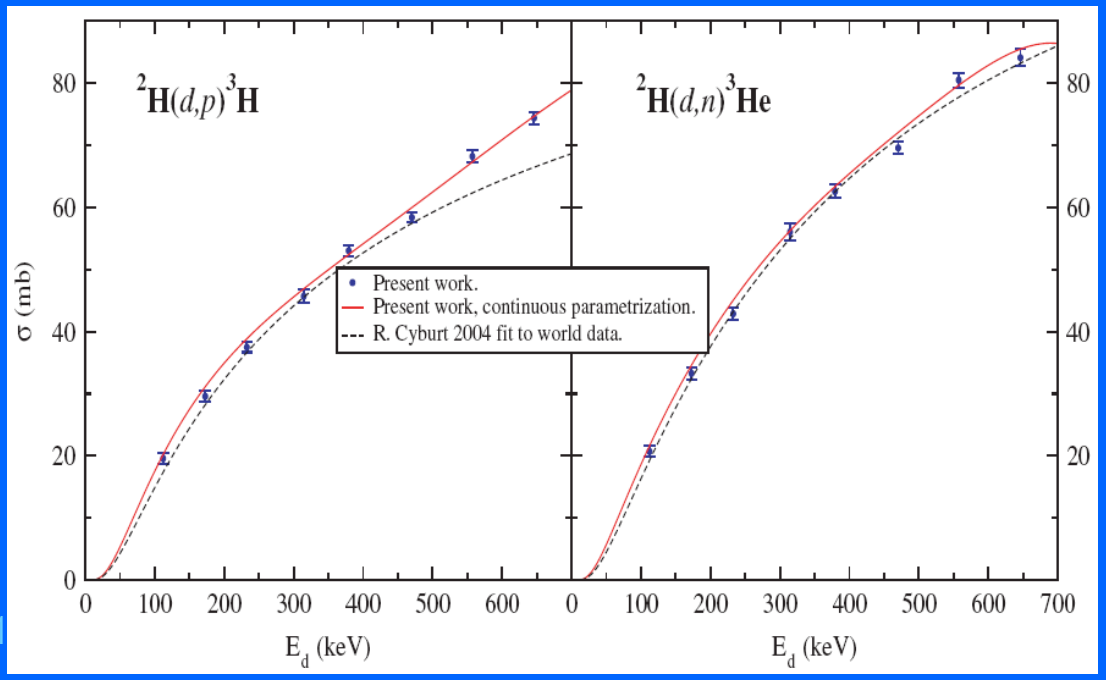
D+D fusion

$d + D \rightarrow p + {}^3H$

$d + D \rightarrow n + {}^3He$

Important: cross sections

Precision measurements @ TUNL



D. Leonard et al., PRC 73 (2006) 045801

D+D fusion

One-spin observables: Analyzing powers

Many experiments @ very low energies

B. Becker et al., Few-Body Systems 13 (1992) 19

Until 2001:

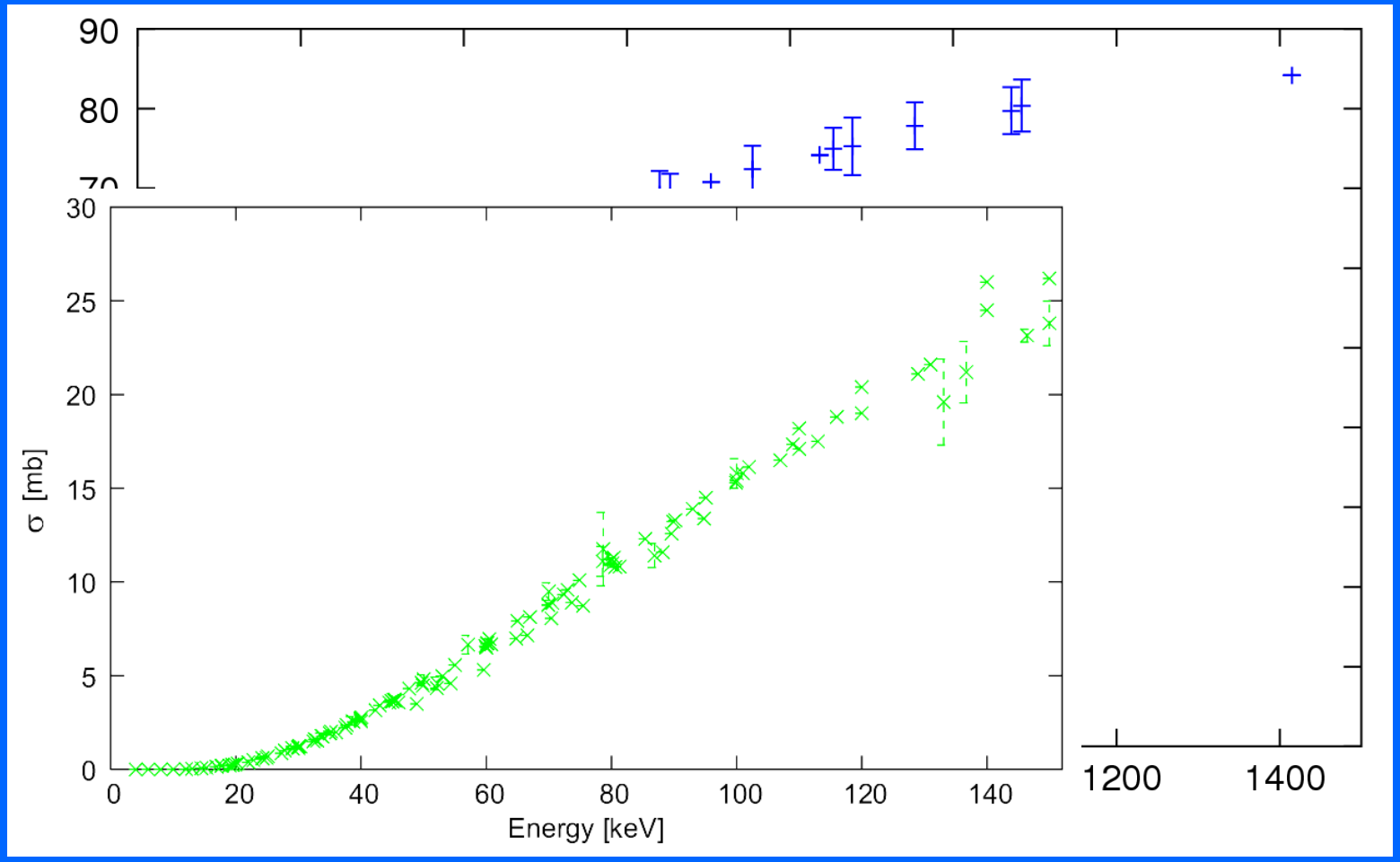
No two-spin observables ≤ 6 MeV

ASTRID @ 58 keV

A measurement of ***S***pin-***TR***ansfer coefficients
In the fusion reaction ***D***$(\vec{d},\vec{p})^3H$

A.I. et al., Phys. Rev. C 73 (2006) 024001

D(d,p)T : Zero-Spin Observable



Two-Spin Observables ?

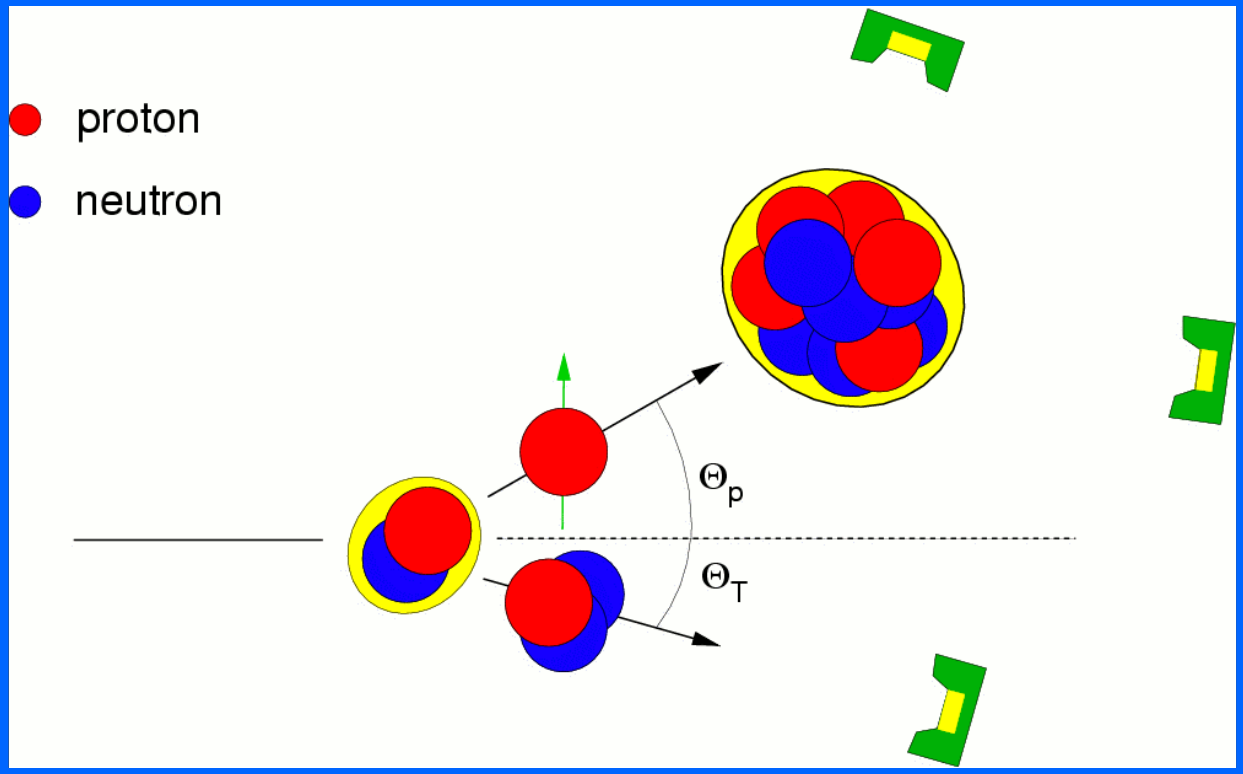
Two-spin observables: Polarization transfer coefficients (PTCs)

Spin correlation:

$\vec{A}(\vec{b},c)D$

Polarization transfer:

$A(\vec{b},\vec{c})D$



Double scattering

➥ **low count rate**

Remedy:

- thick targets
- large solid angles of detectors
- entrance aperture in front of polarimeter

but :

- attenuation of A_y

transfer polarimeter

Analyzer depends on energy range

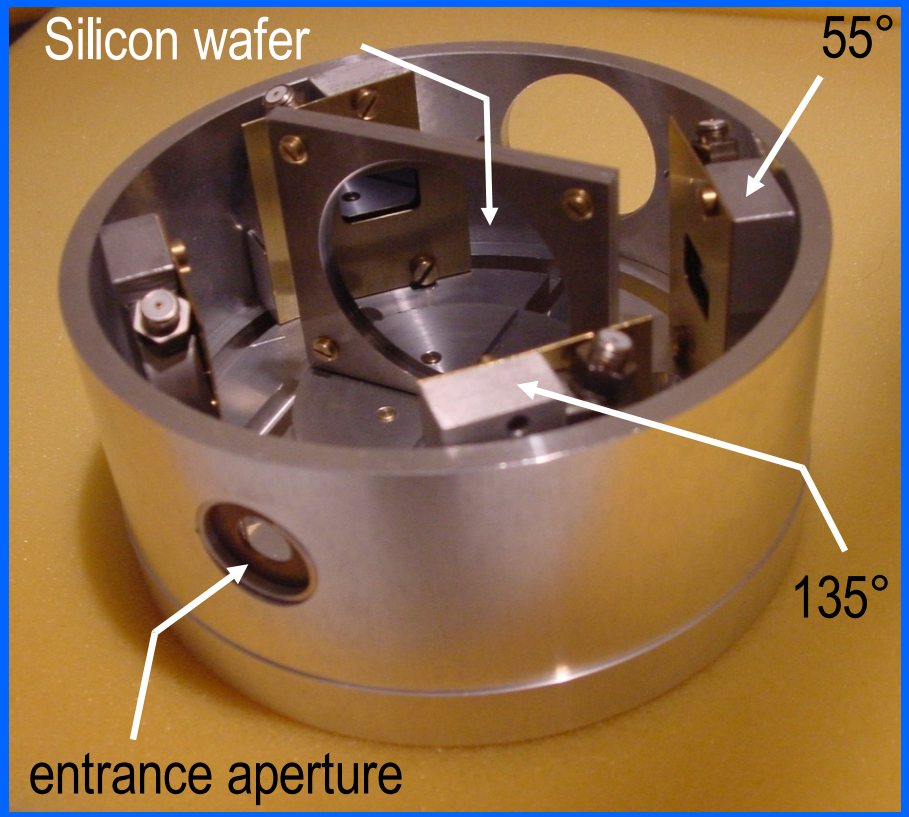
figure of merit : $A_y^2 \cdot \left(\frac{d\sigma}{d\Omega}\right)_0$

protons @ E_p = 3 – 4 MeV :

Si($\vec{p}$,p)Si

detectors : θ = 55°

θ = 135°



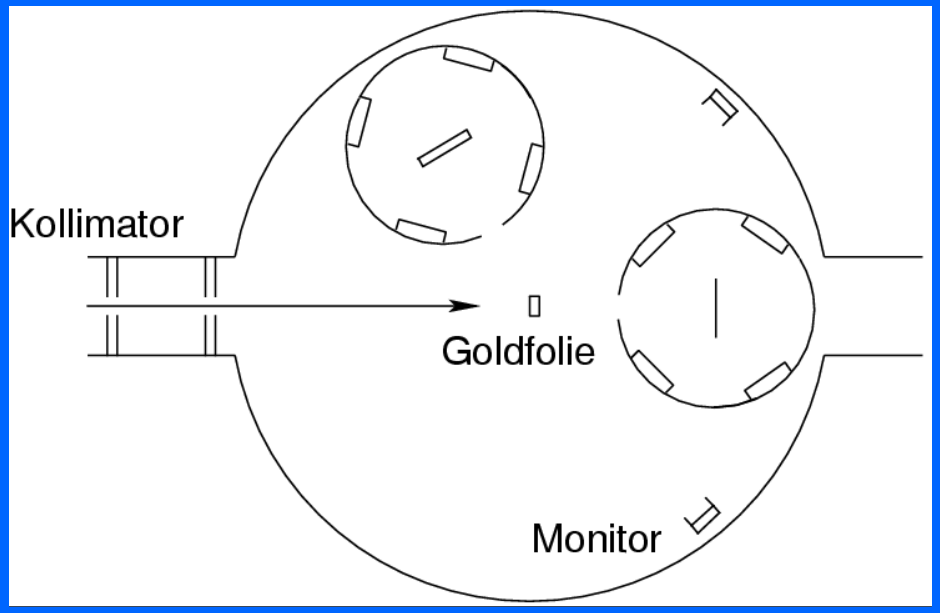
calibration

proton energy range
according to

$D(\vec{d},\vec{p})^3H$ @ $E_d = 58$ keV :

$3.18\ \text{MeV} \leq E_p \leq 3.31\ \text{MeV}$

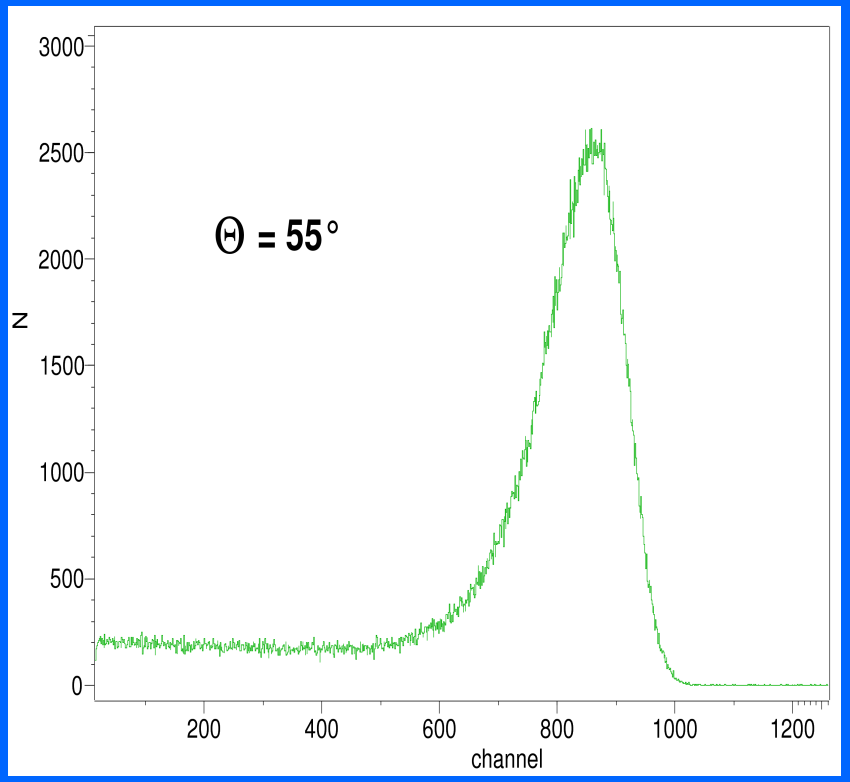
proton beam was directly injected

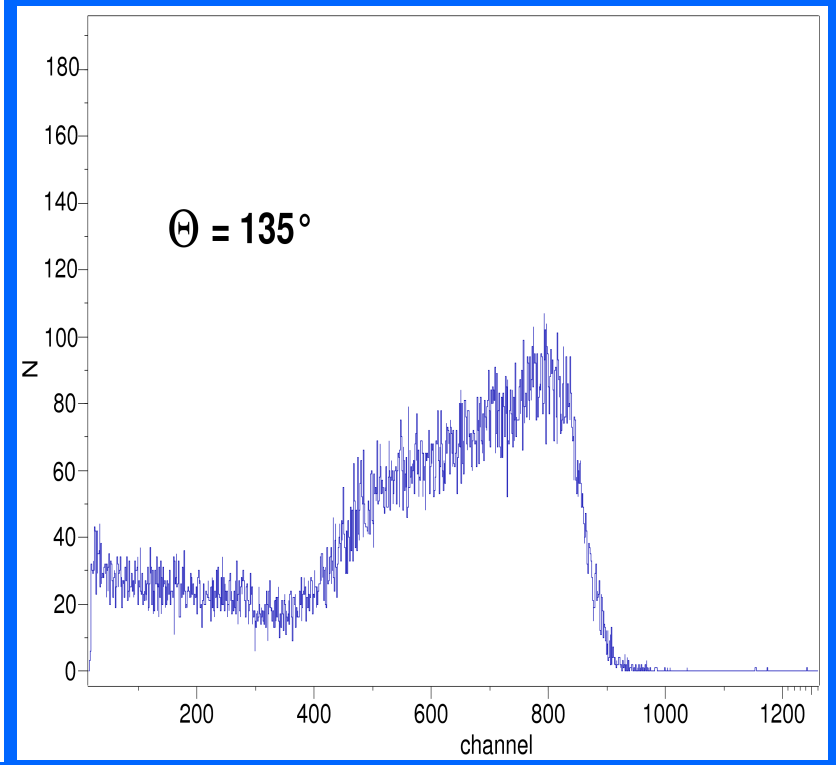


simulating the analyzing reaction:

- spreading the beam by gold foil
- straggling for covering whole entrance aperture

calibration

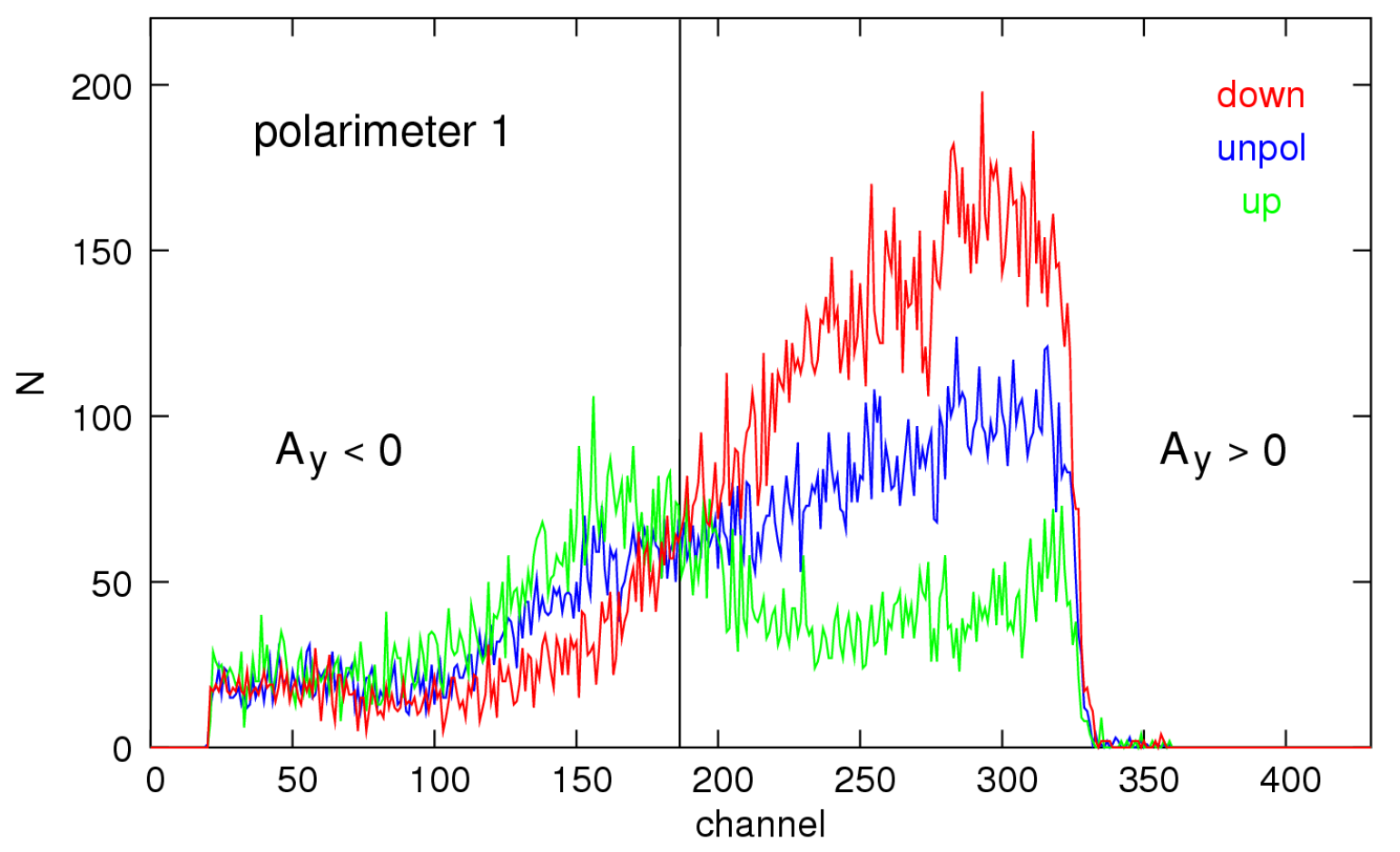




forward

backward

calibration



Double scattering

Results of the calibration:

Polarimeter 1 $A_y = -0.278 \pm 0.002$

Polarimeter 2 $A_y = -0.151 \pm 0.002$

Efficiency of the polarimeters

$$3\text{-}4 \cdot 10^{-5}$$

Other polarimeters :

A.I.	(2001)	^{28}Si	$3.8 \cdot 10^{-6}$	Diplomarbeit
Katabuchi	(2001)	^{28}Si	$9.7 \cdot 10^{-6}$	Phys. Rev. C 64 (2001) 047601
Sydow	(1992)	^{12}C	$3.4 \cdot 10^{-5}$	
Vohl	(1995)	^{3}He	$1.4 \cdot 10^{-6}$	

Targets : polarizer reaction

$(CD_2)_n$

high deuterium loss under bombardment

high energy deposition on the target area

➥ insufficient thermal stability at low energy

energy loss: $E_d = 50$ keV $\quad -\frac{dE}{dx} = 750 \frac{\text{keV}}{\text{mg}\cdot\text{cm}^{-2}}$

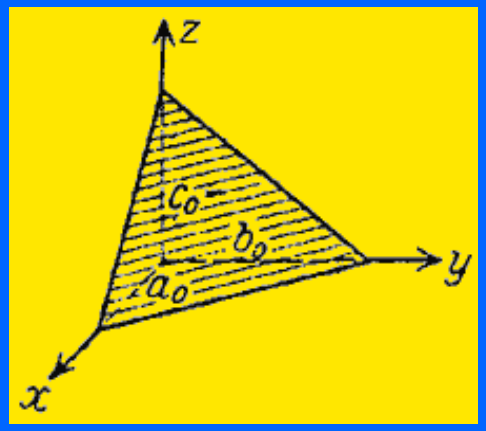
alternative: TiD_2 $\quad -\frac{dE}{dx} = 330 \frac{\text{keV}}{\text{mg}\cdot\text{cm}^{-2}}$

Nucl. Instr. & Meth. 8 (1960) 173

cooling trap with liquid nitrogen

➥ to avoid carbon build up

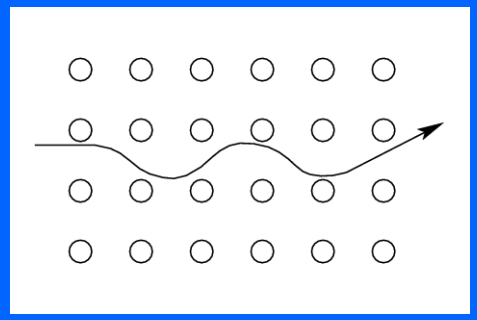
Double scattering

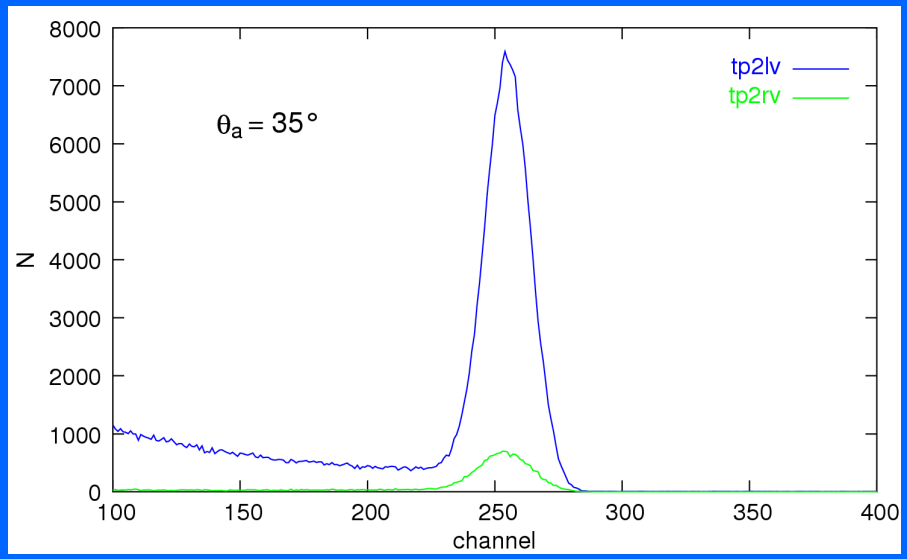


Targets : analyzer reaction

Effects of the crystal structure in Silicon

➥ Channeling

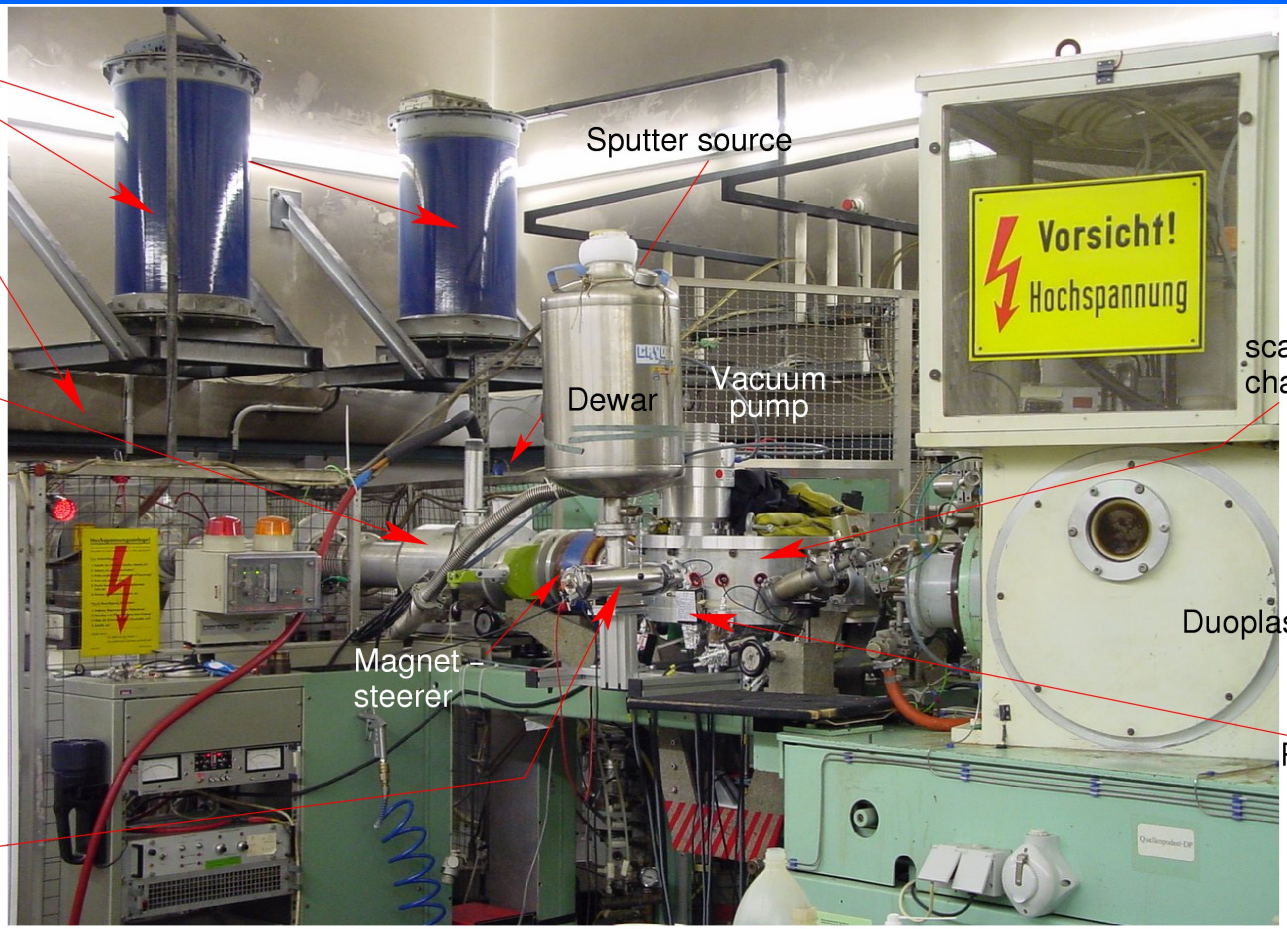




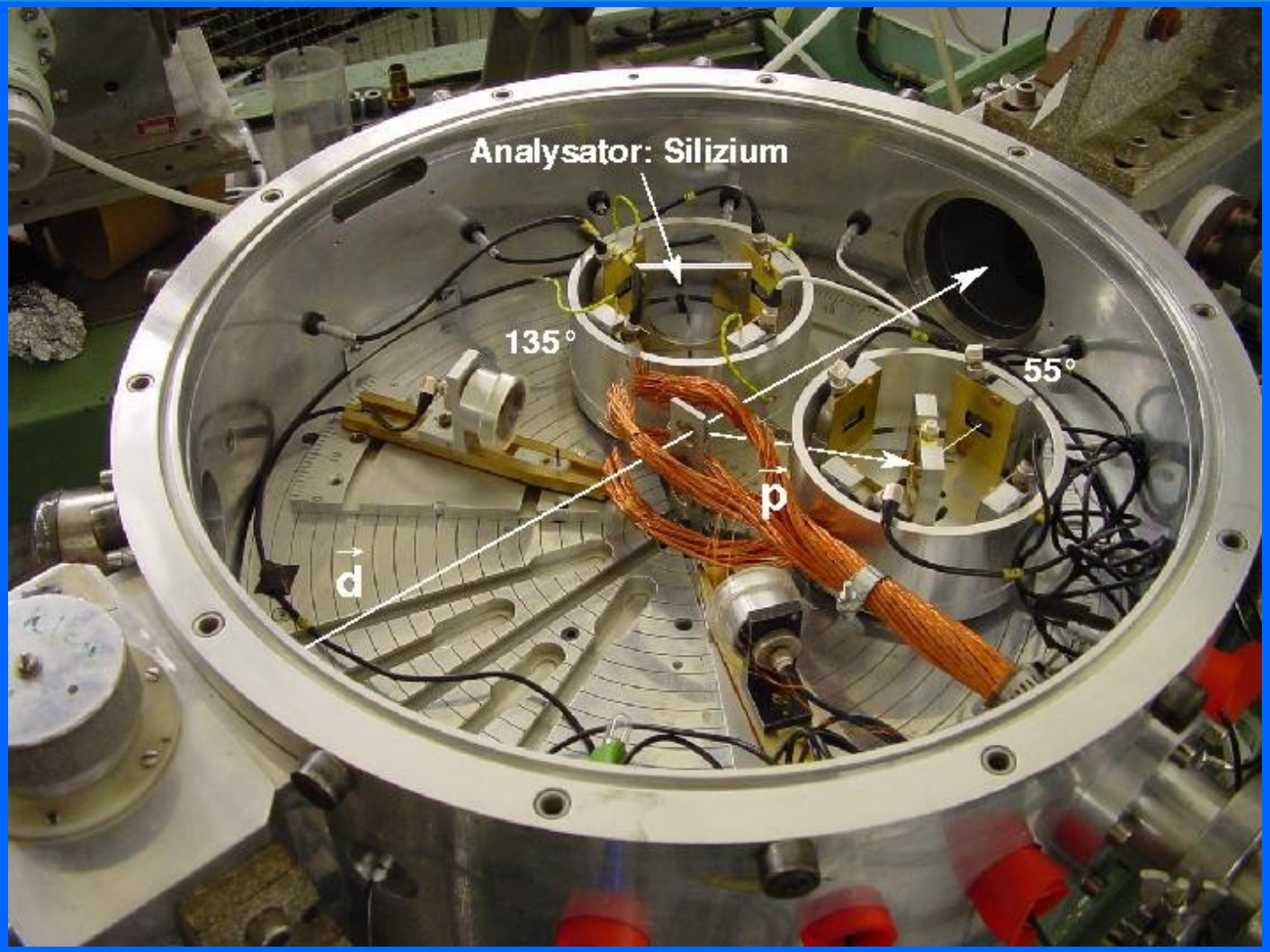
Difference only $\theta_a = 10°$

Unpolarized beam – should be symmetric!

Double scattering

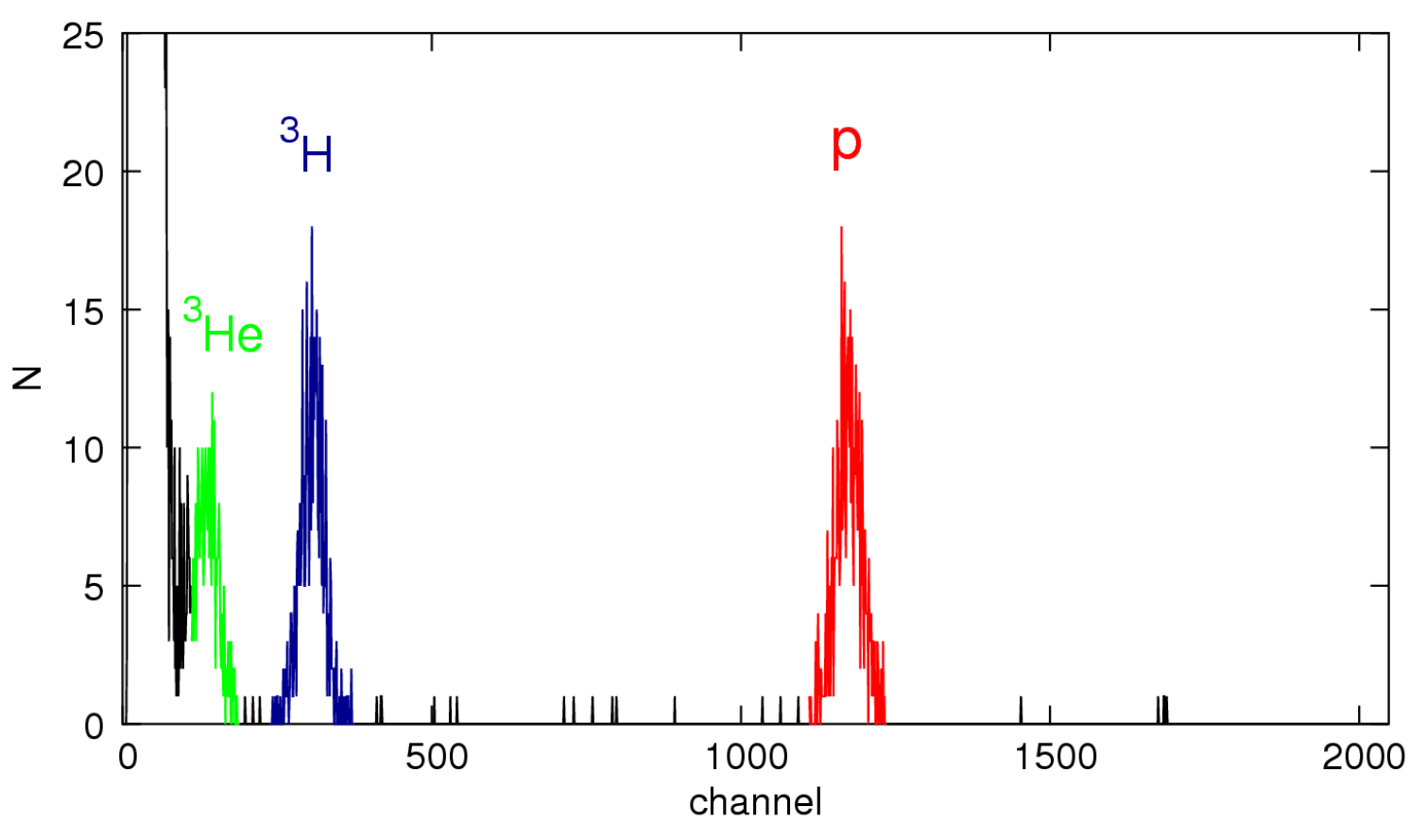


Double scattering



Double scattering

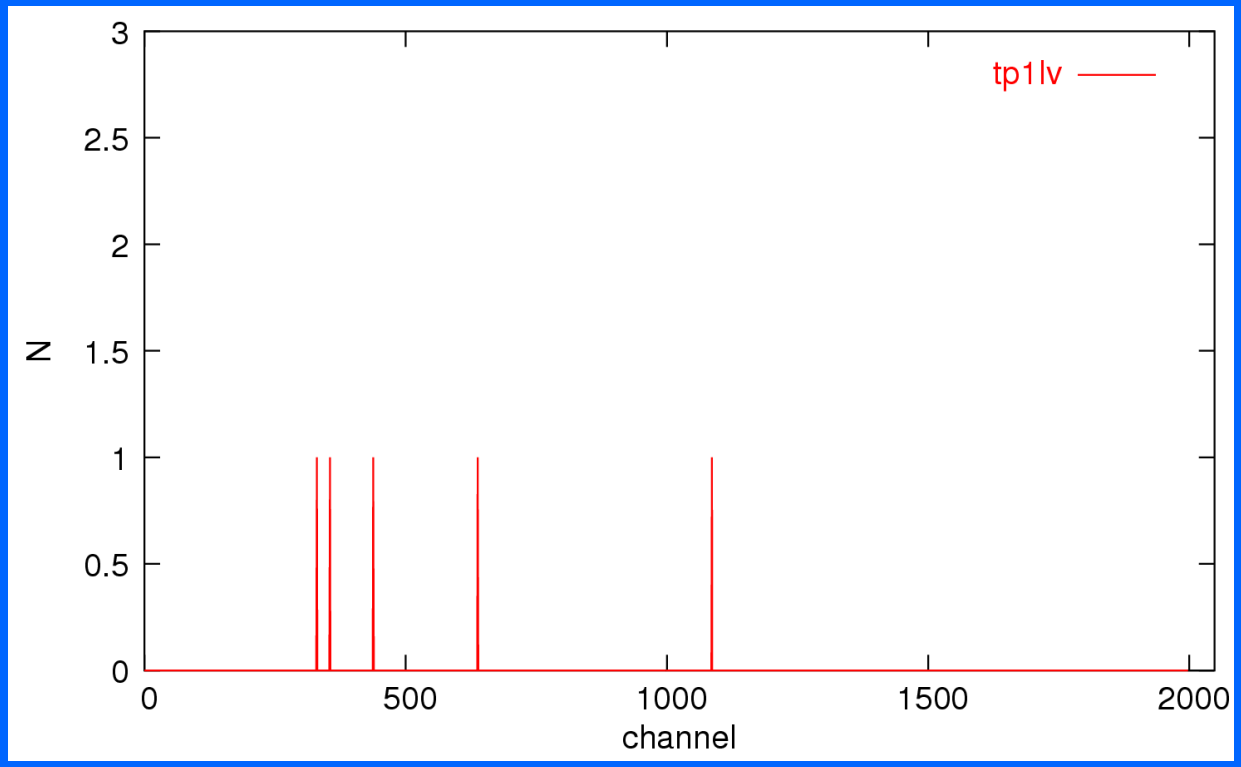
spectrum after first reaction



separation of ^{3}H and ^{3}He by Hostaphan foil

spectrum after second reaction

Where are the protons ?

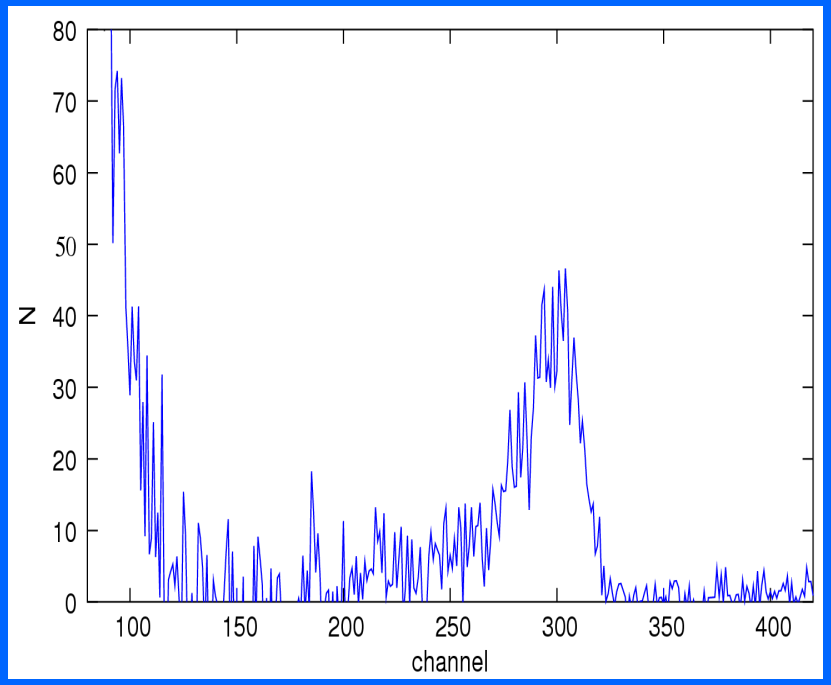


Double scattering

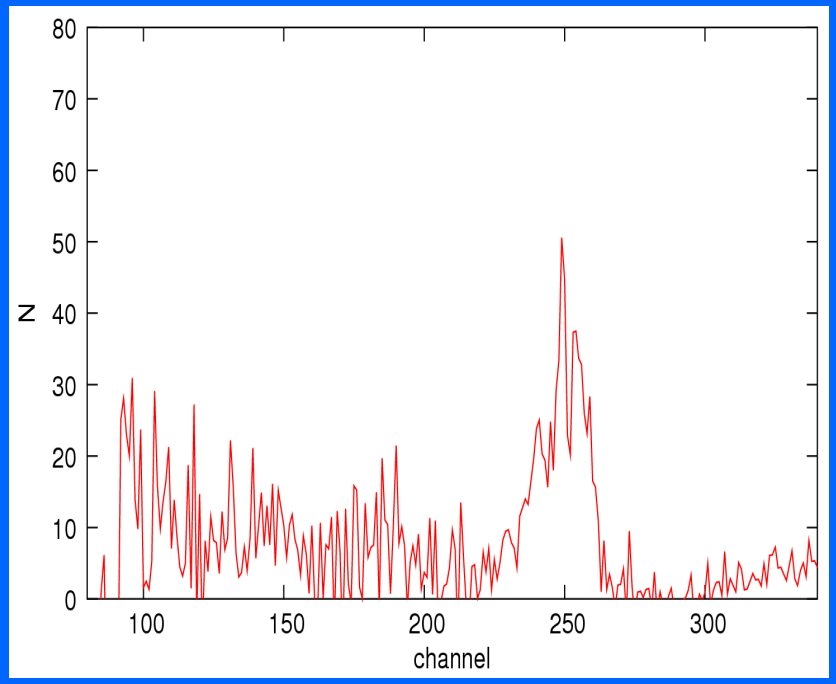
spectrum after second reaction

sum spectra after background reduction

polarimeter 1



polarimeter 2



Determination of PTC

pure vector polarization :

$$K_y^{y'} = \frac{p_{y'}\left(1 + \frac{3}{2} p_y A_y\right) - P^{y'}}{\frac{3}{2} p_y}$$

$$K_y^{y'} = -0.126 \pm 0.186$$

comparison: experiment – experiment

Katabuchi incident energy : E_d = 90 keV, θ = 0°

mean reaction energy :

$\overline{E_R}$ = 68 keV

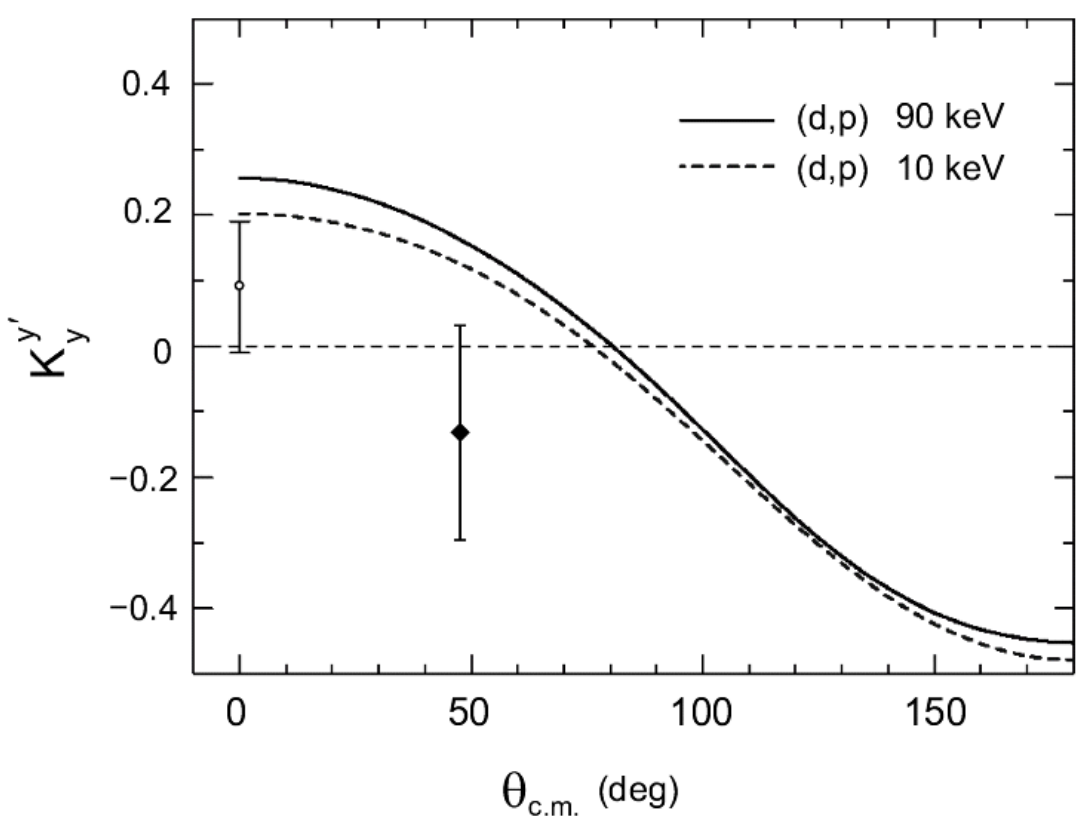
$(CD_2)_n$

A.I. E_d = 78 keV

$\overline{E_R}$ = 58 keV

θ = 45°

TiD_2



Fit over world data set with reaction matrix elements

comparison: experiment – theory

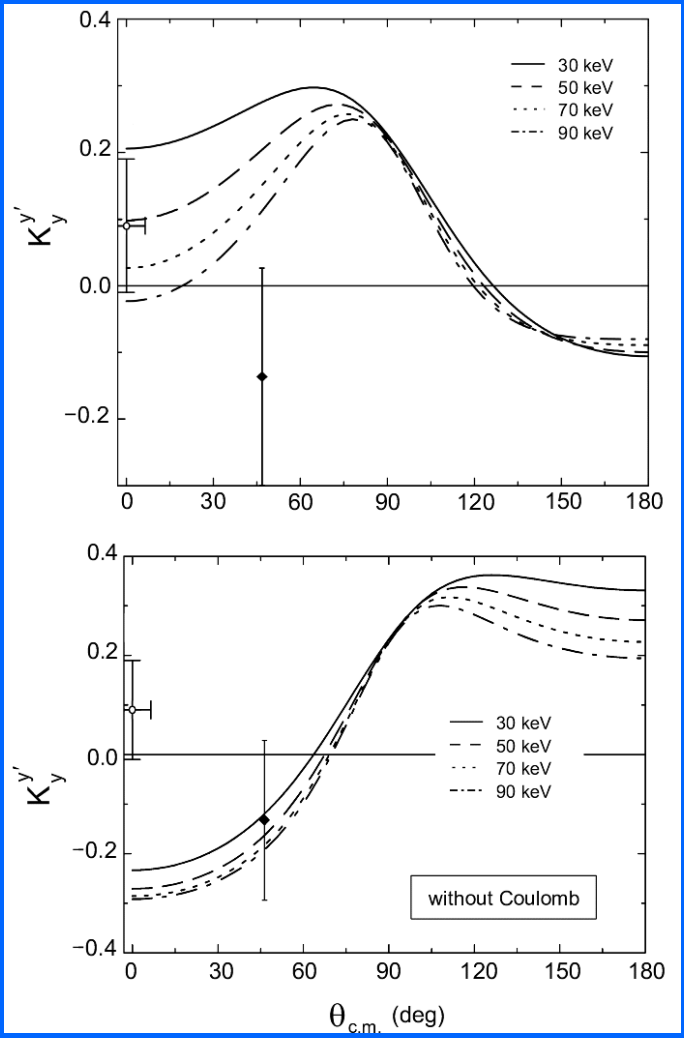
A.I. et al., Phys. Rev. C 73 (2006) 024001

T. Katabuchi et al., Phys. Rev. C 64 (2001) 047601

calculations by Uzu

with and without Coulomb modifications

E. Uzu, arXiv: nucl-th/ 0210026 (2002)

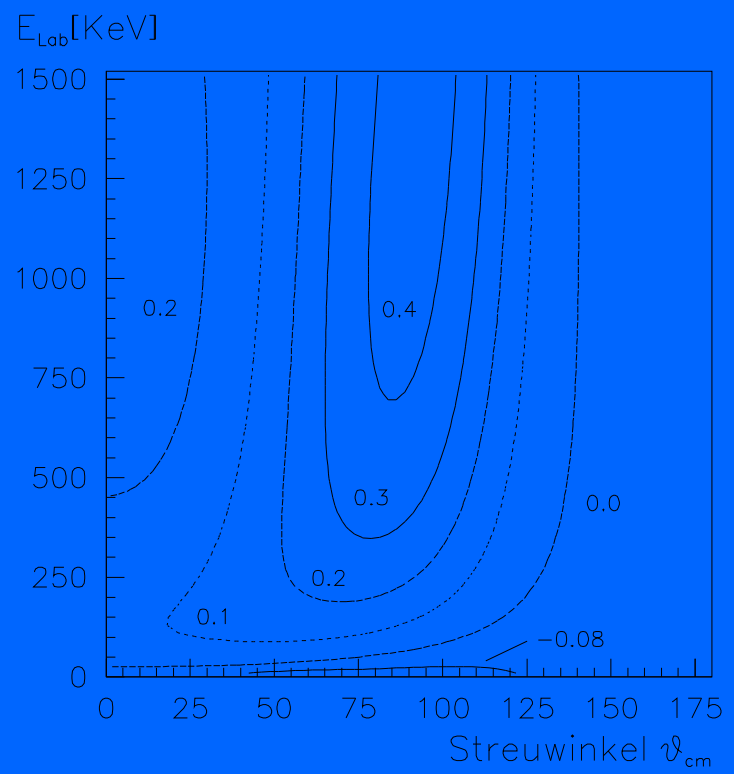


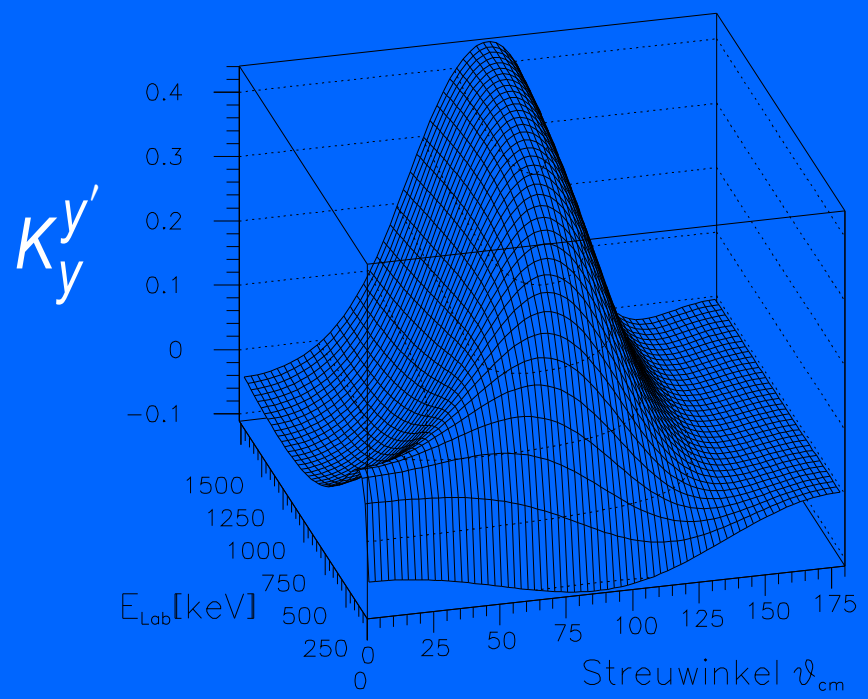
Which could be the correct one ?

Reaction-matrix analysis → predictions for all observables

New calculations are coming

O. Geiger et al., Nucl. Phys. A 586 (1995) 140

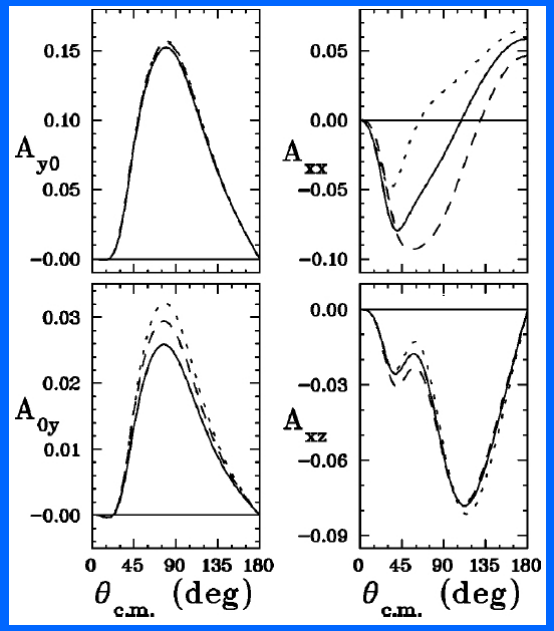




More Two-spin observables: Spin correlation parameters

$^3\overrightarrow{He}(\vec{p},p)^3He$

T. Daniels et al., PhD thesis, in preparation



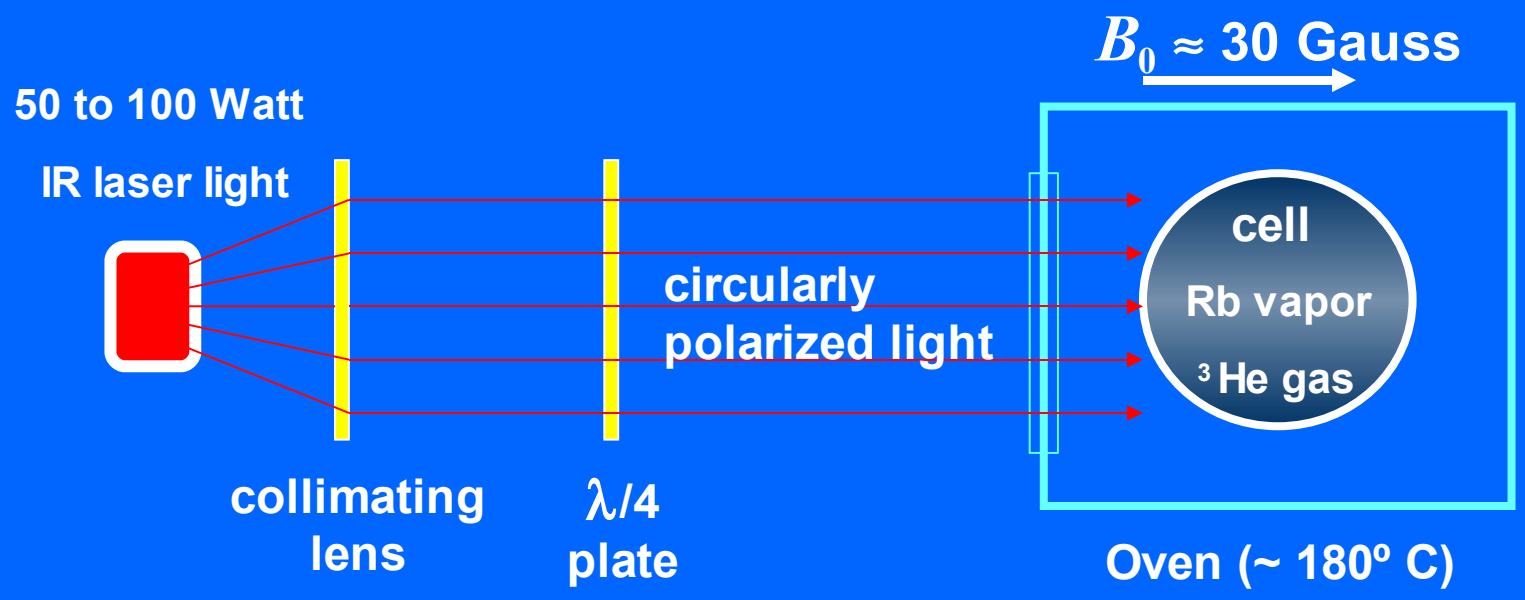
Phase-shift analysis below 12 MeV gives two solutions

E. George, L. Knutson, PRC 67, 027001 (2003)

➥ Two-spin observables needed to clarify !

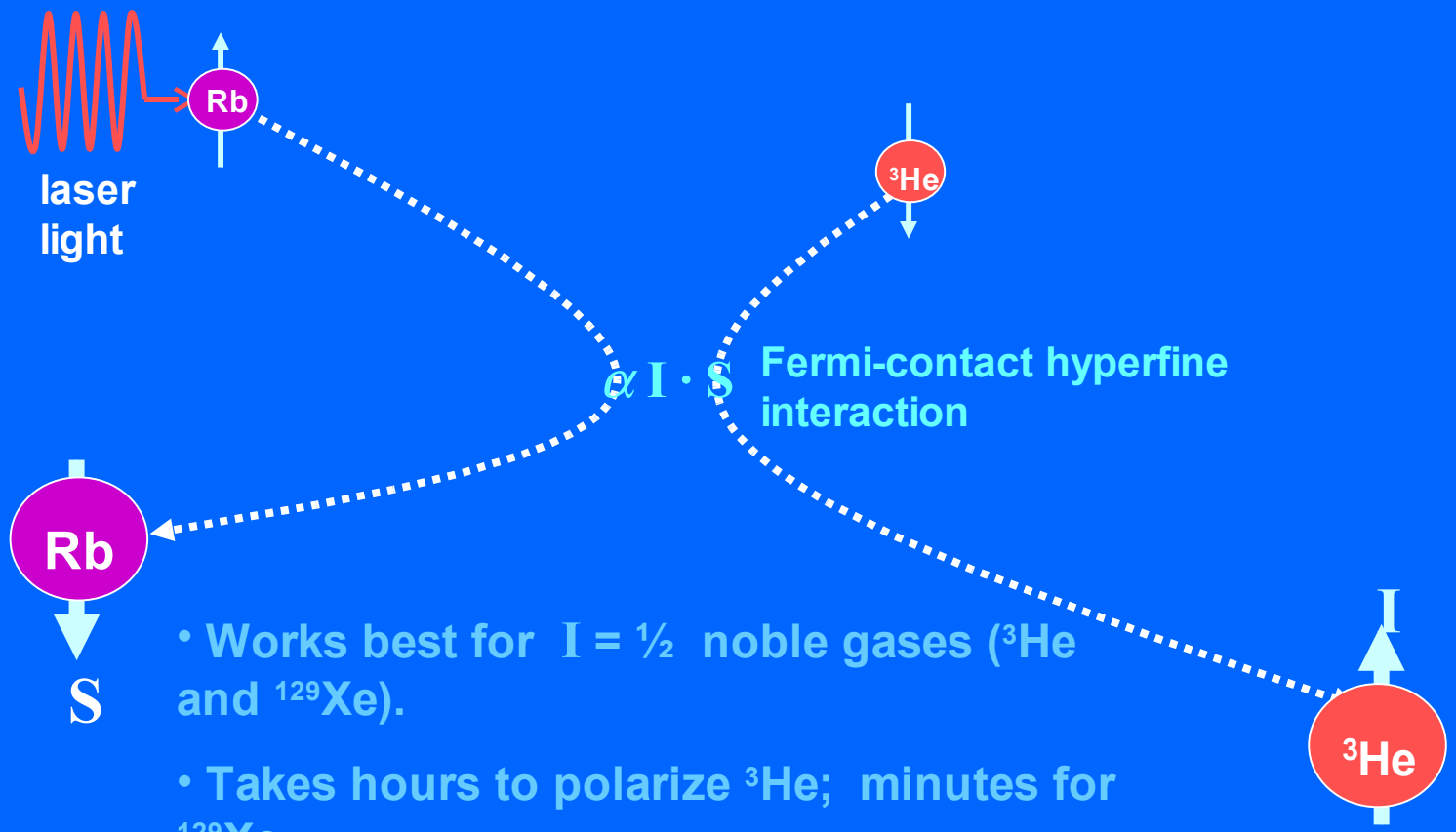
Additional challenges with polarized ^{3}He target …

Schematic of method



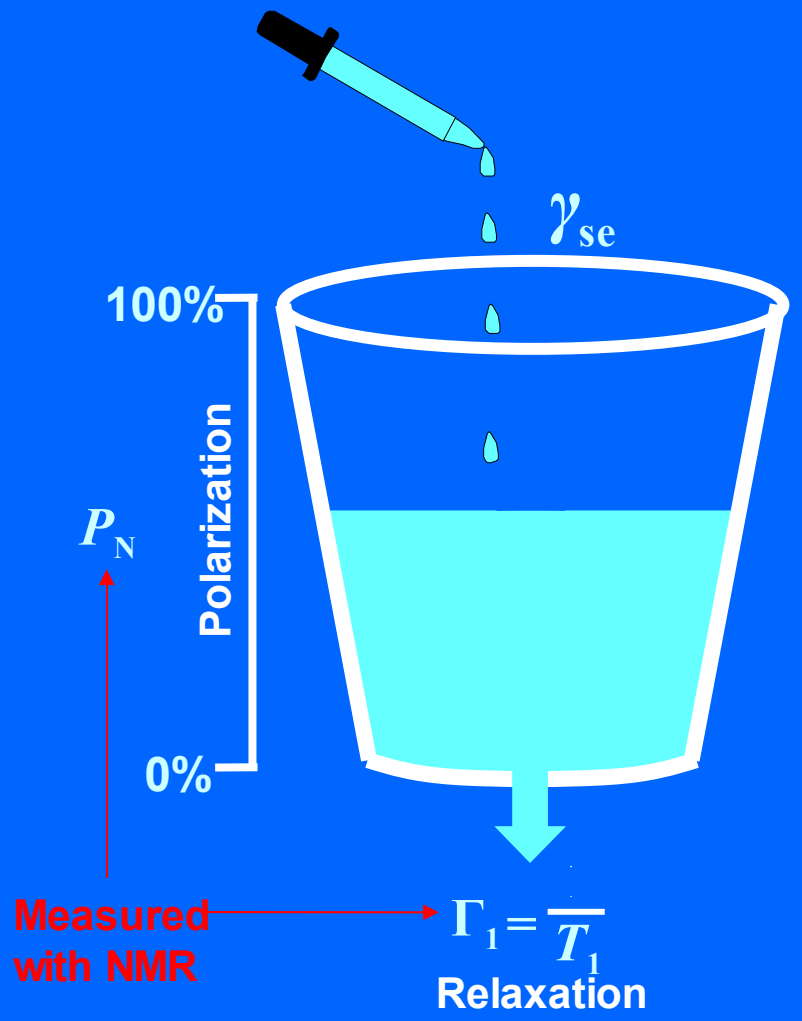
T. Walker, W. Happer, Rev. Mod. Phys. 69, 629 (1997)

Spin-Exchange Collisions



- Works best for $I = ½$ noble gases (^{3}He and ^{129}Xe).
- Takes hours to polarize ^{3}He; minutes for ^{129}Xe.
- Works at cell pressures of up to ~ 10 atmospheres

Polarizing ^{3}He - Filling the Bucket



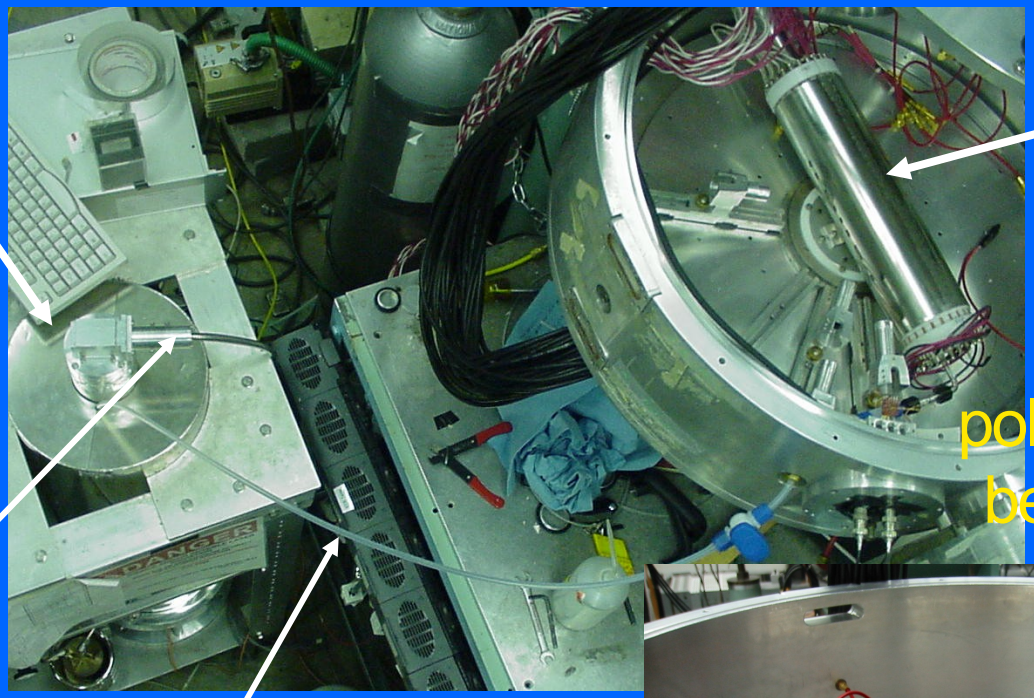
$$\gamma_{se} = [\mathrm{Rb}]\,\langle \sigma_{se} v \rangle$$

$$P_{3He} = \langle P_{Rb} \rangle \left(\frac{\gamma_{se}}{\gamma_{se} + \Gamma_1} \right)$$

$$\frac{1}{T_1} = \frac{1}{T_B} + \frac{1}{T_{gas}} + \frac{1}{T_{wall}}$$

T_1 is ***usually*** dominated by wall interactions…

Polarized ^{3}He Targetry at TUNL



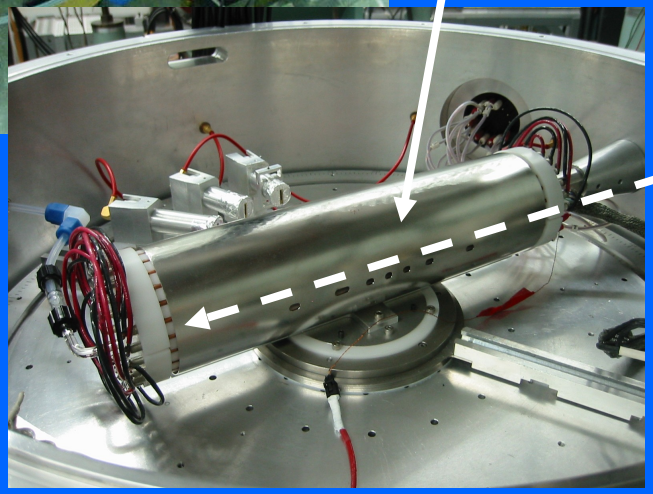
SEOP Polarizer (8 ATM OP cell inside)

60 W fiber-coupled diode laser

Polarized ^{3}He target inside sine-theta coil

Incident polarized proton beam direction

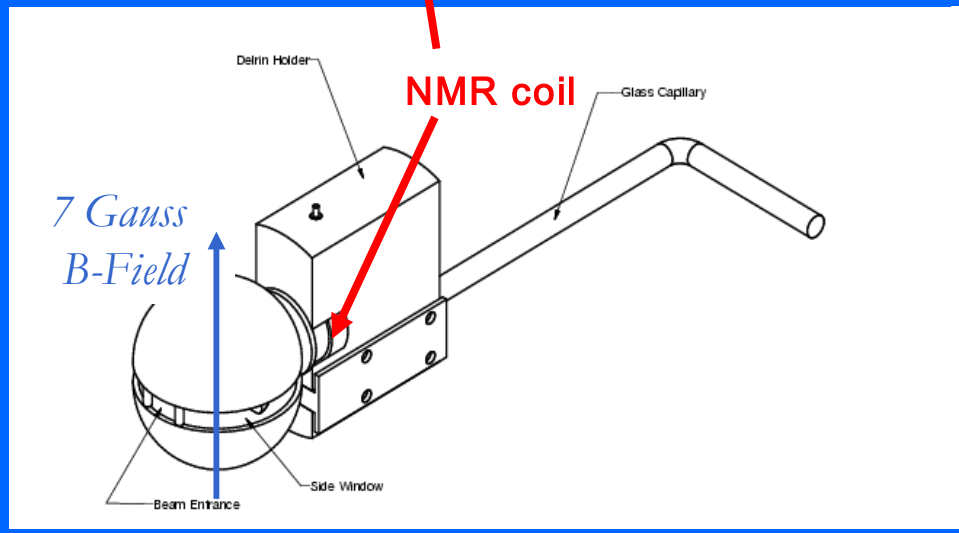
Polarized ^{3}He dispense tube

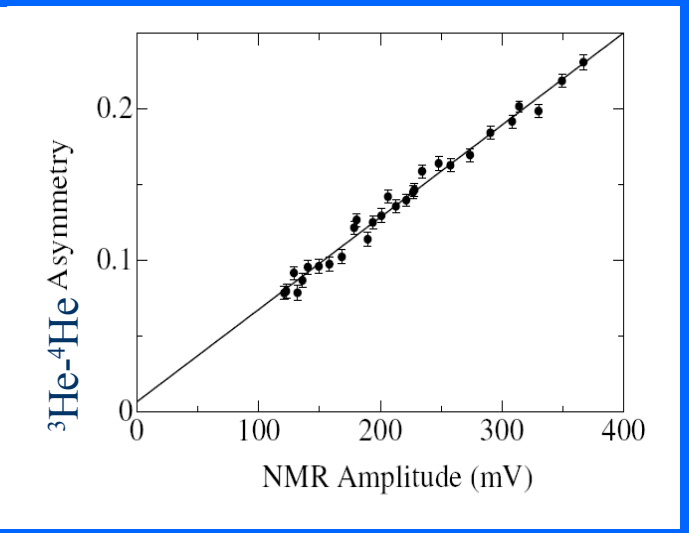


T. Katabuchi et al., Rev. Sci. Instrum. 76, 033503 (2005)

Absolute ^{3}He Polarimetry

- Pyrex glass cell with Kapton windows
- ^{3}He pressure ~1 ATM; P ~25 to 30%
- NMR to monitor ^{3}He target polarization
- Calibrate NMR by ^{4}He + ^{3}He scattering
- Polarization 1/e lifetime ~ 2 hrs

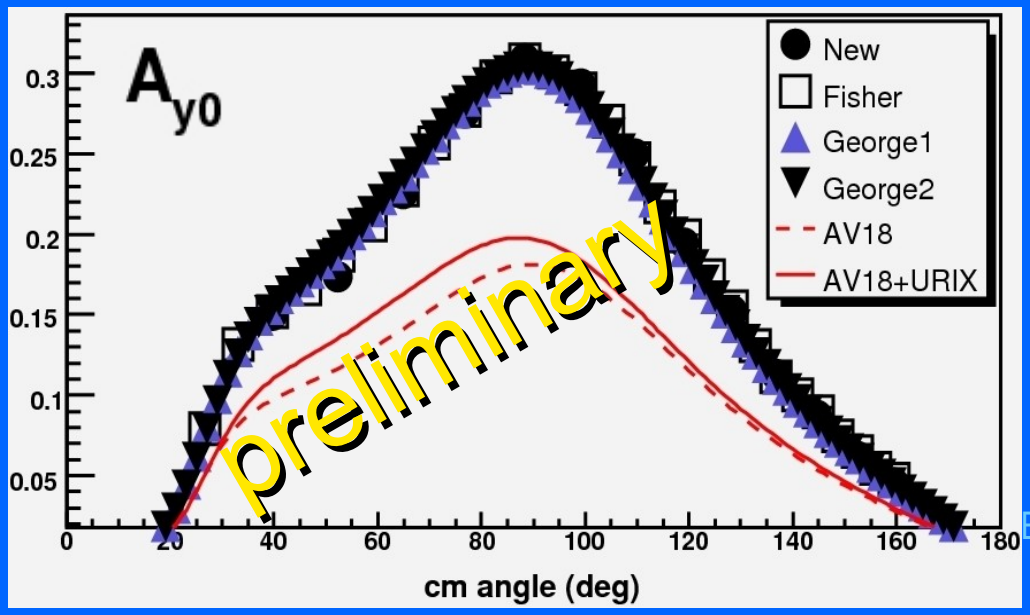




Preliminary results for E_p = 3.16 MeV

T. Daniels, Al, et al., PhD thesis, in preparation

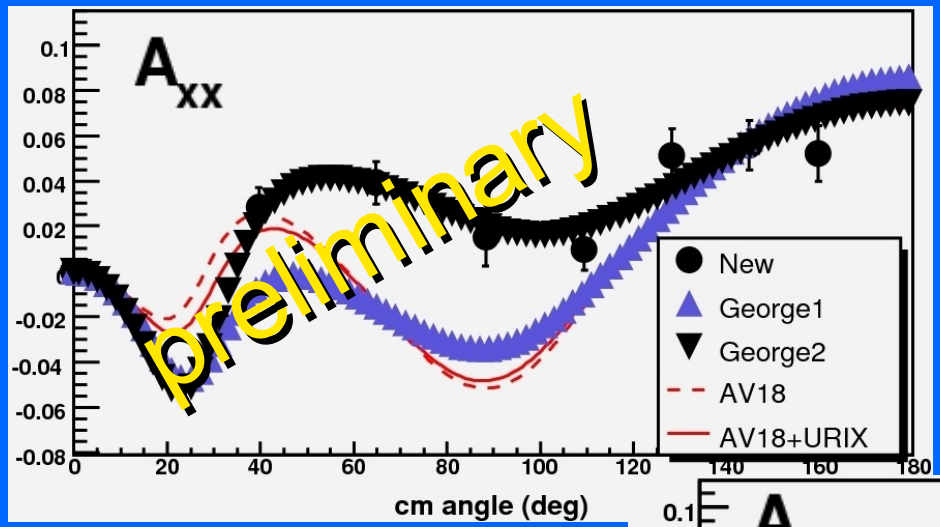
Data of Fisher used for normalization



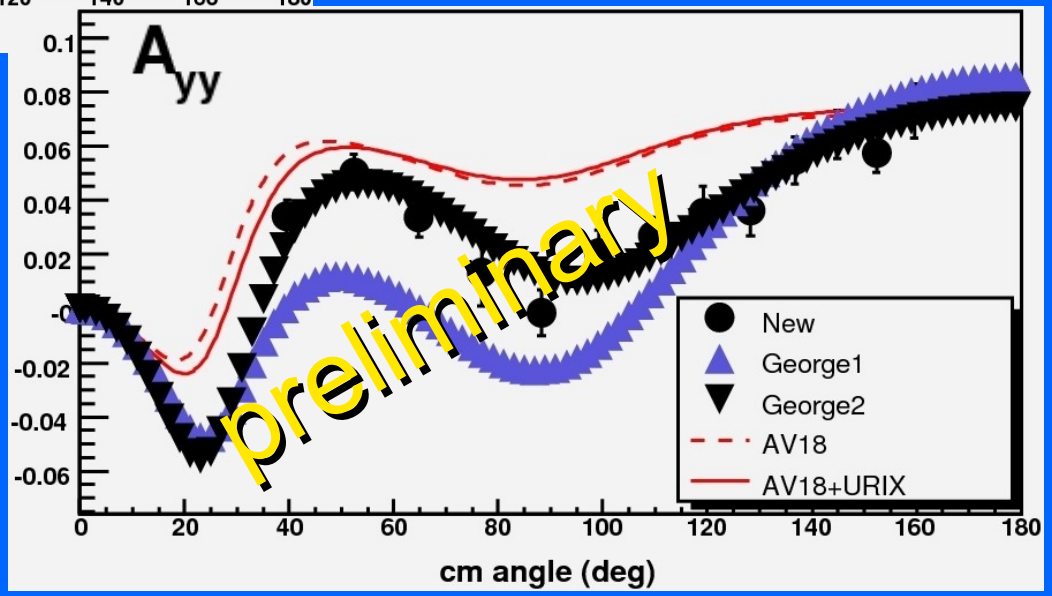
E. George, L. Knutson, PRC 67, 027001 (2003)

B. Fisher et al., PRC 74, 034001 (2006)

Analysis

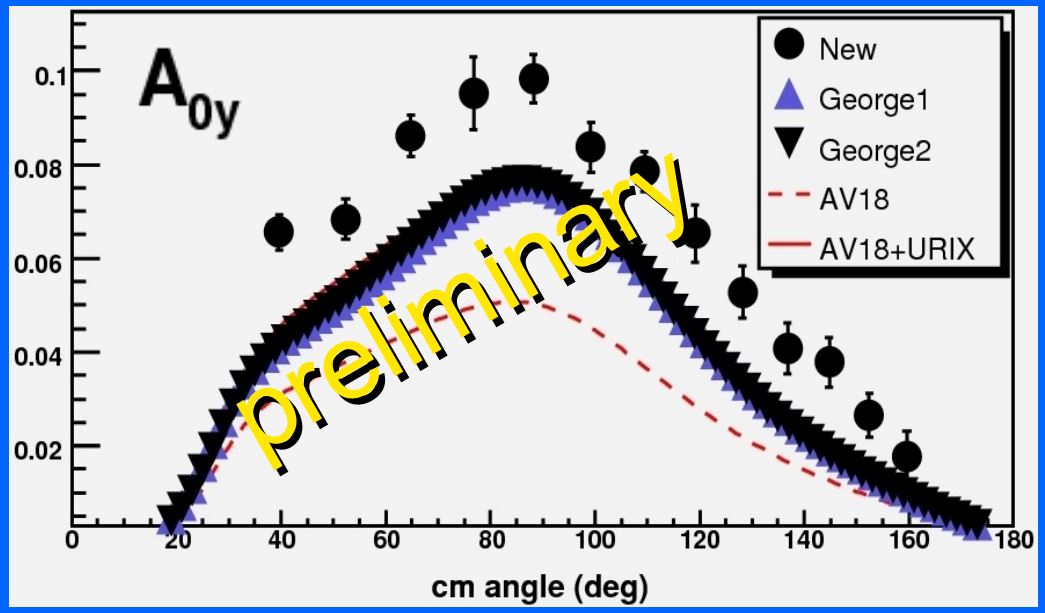


Preliminary results for E_p = 3.16 MeV

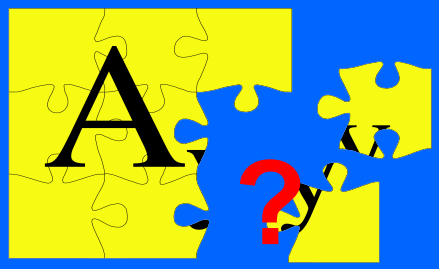


Preliminary results for E_p = 3.16 MeV

Corrections are still to be made for systematic errors:
Magnetic field shifts the proton beam



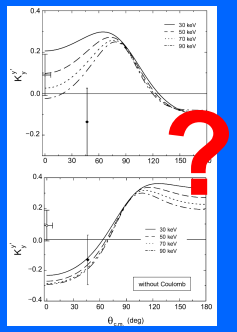
summary

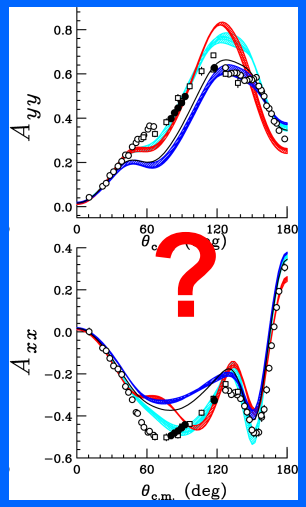


Many Observables have been measured

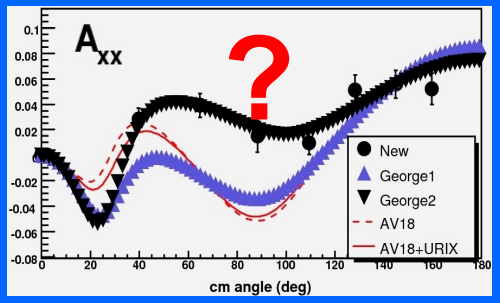
3N system ✓

4N system ✓





Theory ?



➥ **Further progress in theory is needed !**

acknowledgments

- H. Paetz gen. Schieck
- C. Düweke
- J. Ley
- V. Werner
- G. Pascovici
- K.-O. Zell

- H. Karwowski
- T. Clegg
- C. Howell
- T. Daniels
- A. Couture