Unsolved Problems in Few-Nucleon Scattering at Low Energies

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Are there any unsolved problems?

Clearly, there are some.

Are they real ?

If yes,
are they relevant ?

If yes,
should we invest time and resources to fix them,
or
should we move on?

Outline

- Introduction

- A=2 systems

  n-n and n-p scattering

- A=3 systems

  p-d and n-d elastic scattering and breakup

- A=4 systems

  p-^{3}He, n-^{3}He, and p-^{3}H elastic scattering

- Conclusions

Energy range considered: $\leq$ 50 MeV/N

A=2 Neutron-neutron scattering length a_{nn}

Researchers at TUNL have been involved in determinations of a_{nn} during the past 25 years using the reactions

^{2}H(π^-,γn)n at LAMPF $a_{nn}=-18.5 \pm 0.4$ fm (stat) $\pm$ 0.3 (syst)

C.R. Howell et al., Phys. Lett. B **444**, 252 (1998)

^{2}H(n,nn)p at TUNL $a_{nn}=-18.7 \pm 0.6$ fm

D.E. Gonzalez Trotter et al., Phys. Rev. Lett. **83**, 3788 (1999)

But W. von Witsch got consistently smaller values using

^{2}H(n,np)n at Bonn $a_{nn}=-16.1 \pm 0.4$ fm and -16.3 ± 0.4 fm

V. Huhn et al., Phys. Rev. C **63**, 014003 (2000)

Real? Yes

Relevant? Probably not

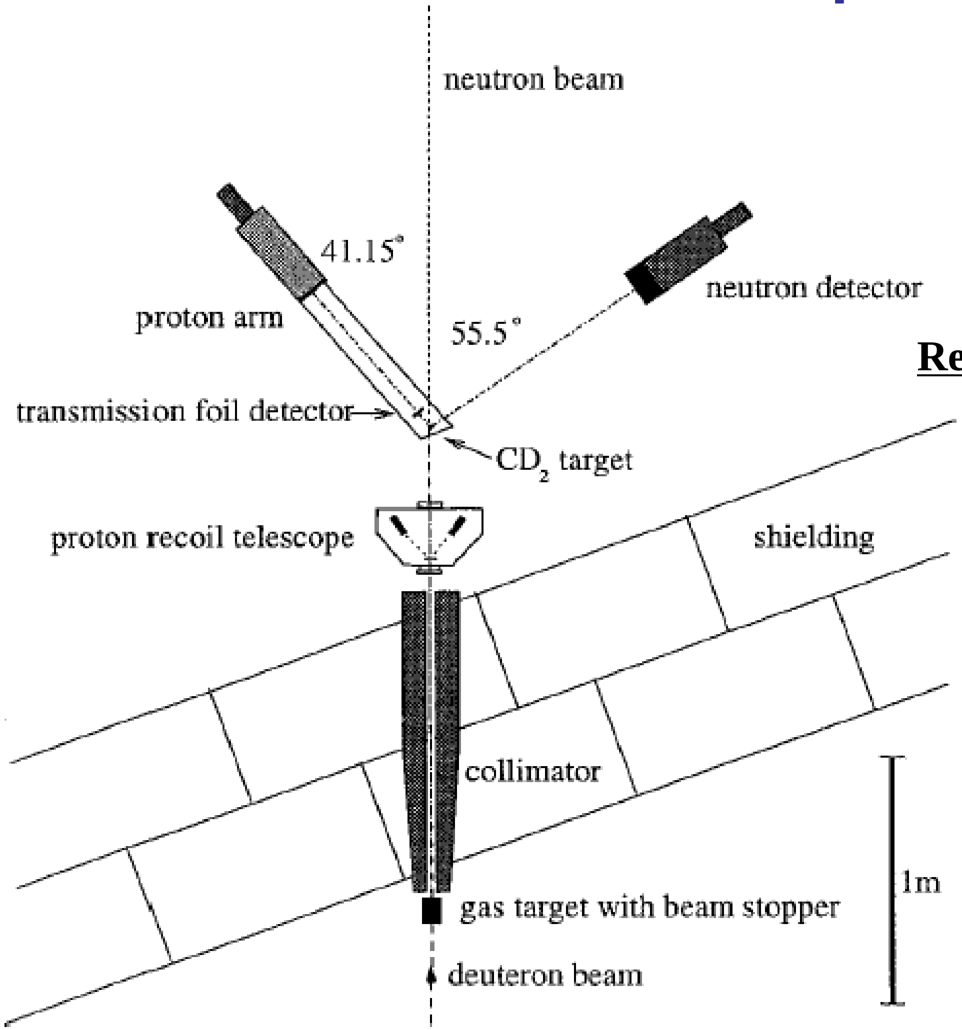
Fix it? Maybe

A=2 Neutron-neutron scattering length a_{nn}

C.R. Howell *et al.* teamed up with W. von Witsch to redo the a_{nn} measurement at E_n=19 MeV using ^{2}H(n,np)n at TUNL, and the Bonn apparatus

A=2 Neutron-neutron scattering length a_{nn}

Recoil Setup at University of Bonn



$E_n = 25.3$ MeV

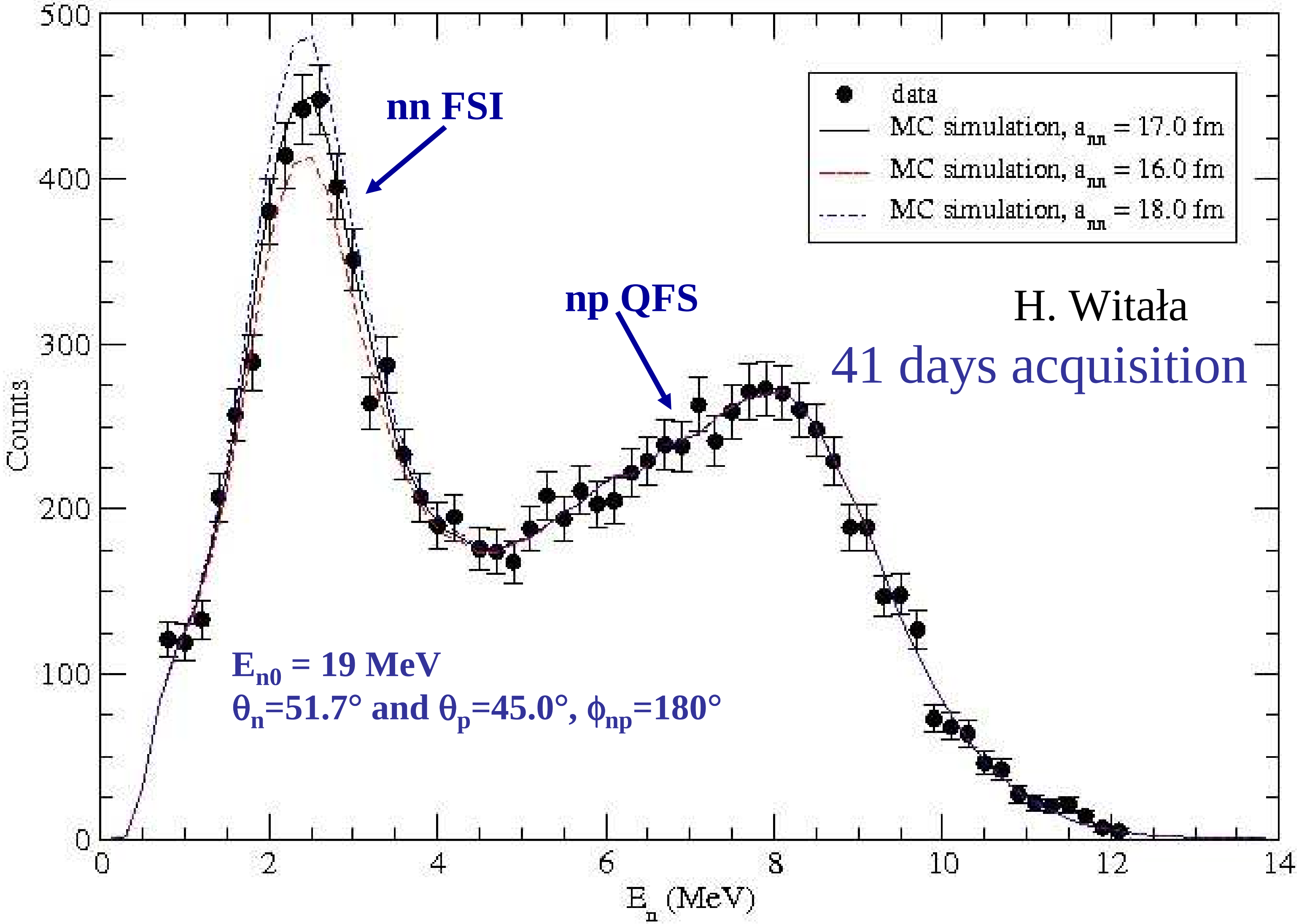
Recoil Geometry Technique

(a) thin target (CD2)
(b) detect one FSI neutron with recoil proton
(c) depends on efficiency of only one neutron detector
(d) modest neutron attenuation corrections
(e) account for finite geometry effects

$a_{nn} = -16.2 \pm 0.4$ fm, V. Huhn et al., Phys. Rev. C 63, 014003-1 (2000)

A=2 Neutron-neutron scattering length a_{nn}

E_n spectrum normalized to nd elastic scattering



A=2 Neutron-neutron scattering length a_{nn}

Ultimate Goal: Direct n-n Scattering

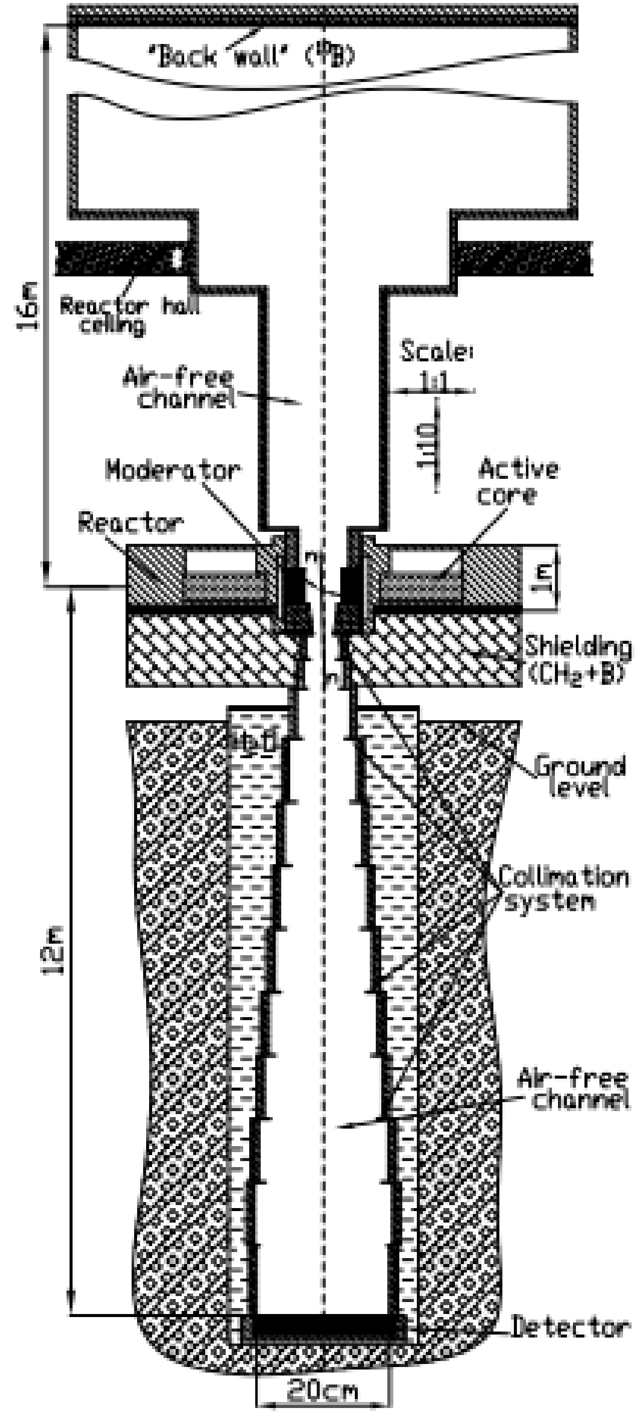
Collaboration: Joint Institute of Nuclear Physics, Dubna
All Russian Institute of Technical Physics, Snezhinsk
TUNL

Pulsed reactor YAGUAR: neutron flux ~10^{18} /cm^{2}s, 1000 μs pulse

Project funded by the International Science and Technology Center (ISTC)

A=2 Neutron-neutron Scattering length a_{nn}

YAGUAR
Reactor



A=2 Neutron-neutron scattering length a_{nn}

Basic idea: Measure number of thermal neutrons as a function of the reactor power in a collimated detector using neutron time-of-flight.
The n-n scattering signal should increase with the power squared, while the background should increase linearly.
At full reactor power one expects about 170 neutron counts during one burst. There are 10^{13} neutrons/cm^3 during the pulse.

Measurements were done at different reactor powers with helium in the chamber and results were compared to Monte-Carlo simulations: good agreement was found.

A=2 Neutron-neutron scattering length a_{nn}

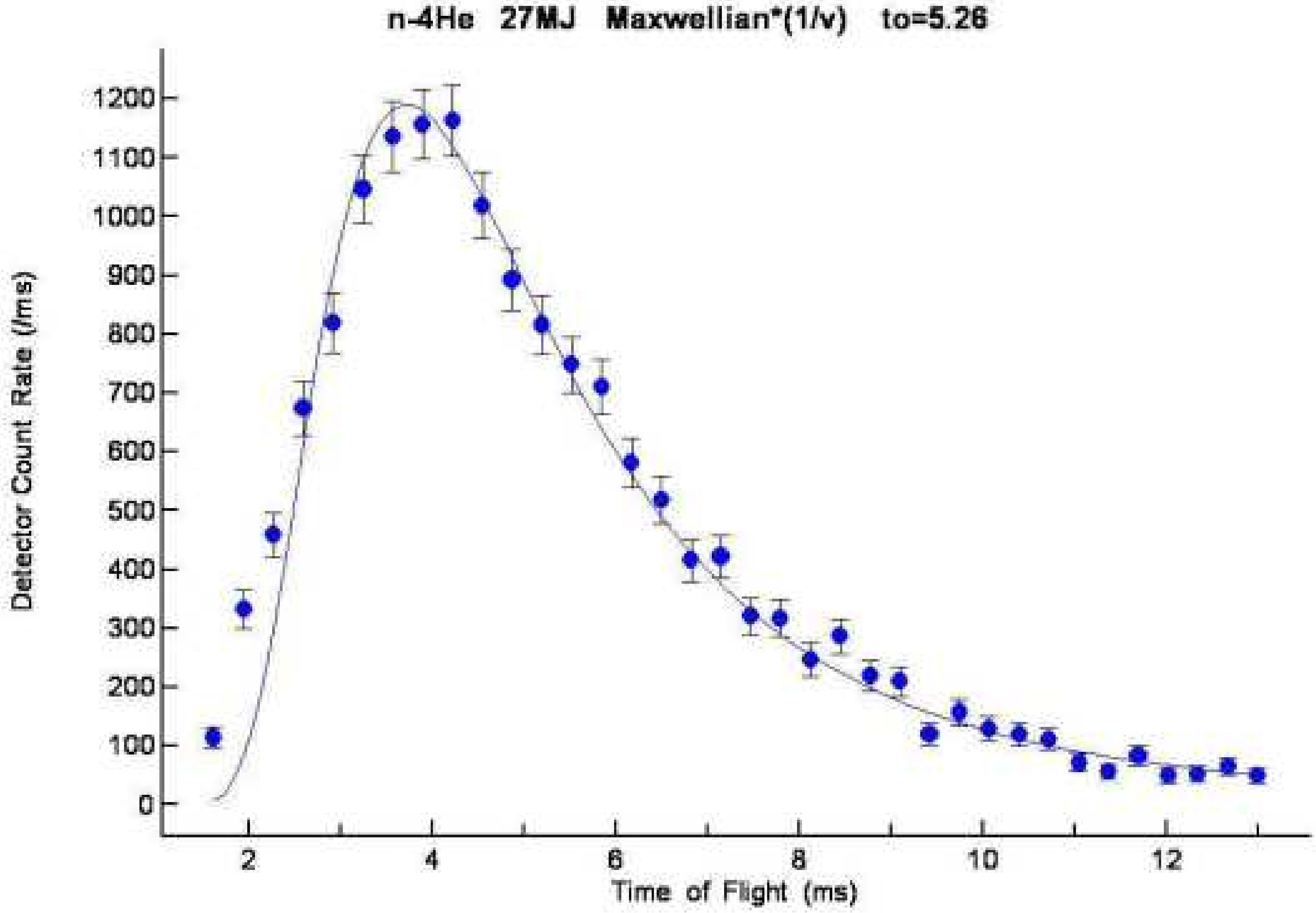


Figure 4: Time-of-flight data (12 m) for a (n^4He) run produced during a 27 MJ YAGUAR reactor pulse. The solid curve represents the fit to the data, taking into consideration the $1/v$ dependence of the detector efficiency as well as a Maxwellian velocity distribution.

A=2 Neutron-neutron scattering length a_{nn}

Experiment failed !!!

S.L. Stephenson et al., Nucl. Phys. A **895**, 33 (2012)

Unforeseen significant thermal neutron background as a result of radiation induced desorption (outgassing) within the scattering chamber.
Thermal neutrons are mostly scattered not from other neutrons, but instead from desorbed gas molecules, mostly H_2.

A=2 Neutron-neutron scattering length a_{nn}

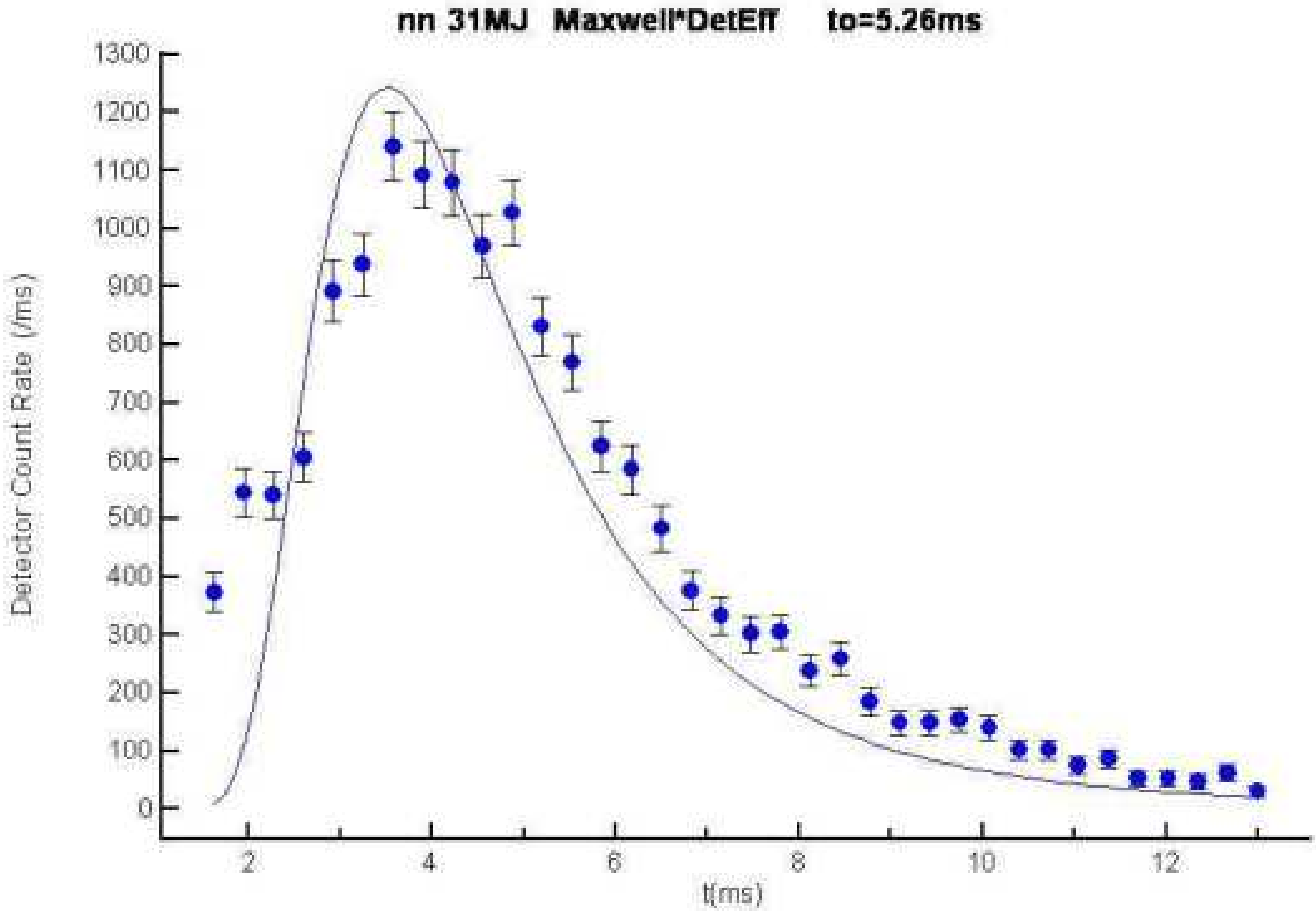


Figure 1: The data points represent time-of-flight data for neutron-neutron scattering at a reactor pulse energy of 31 MJ and a 12 meter flight path. The overall count rate is approximately 30 times higher than predicted. The relatively poor fit (solid curve) demonstrates the inability to fit the data with only a Maxwellian (with a most probable neutron speed of 2200 m/s) and the appropriate detector efficiency.

A=2 Neutron-neutron scattering length a_{nn}

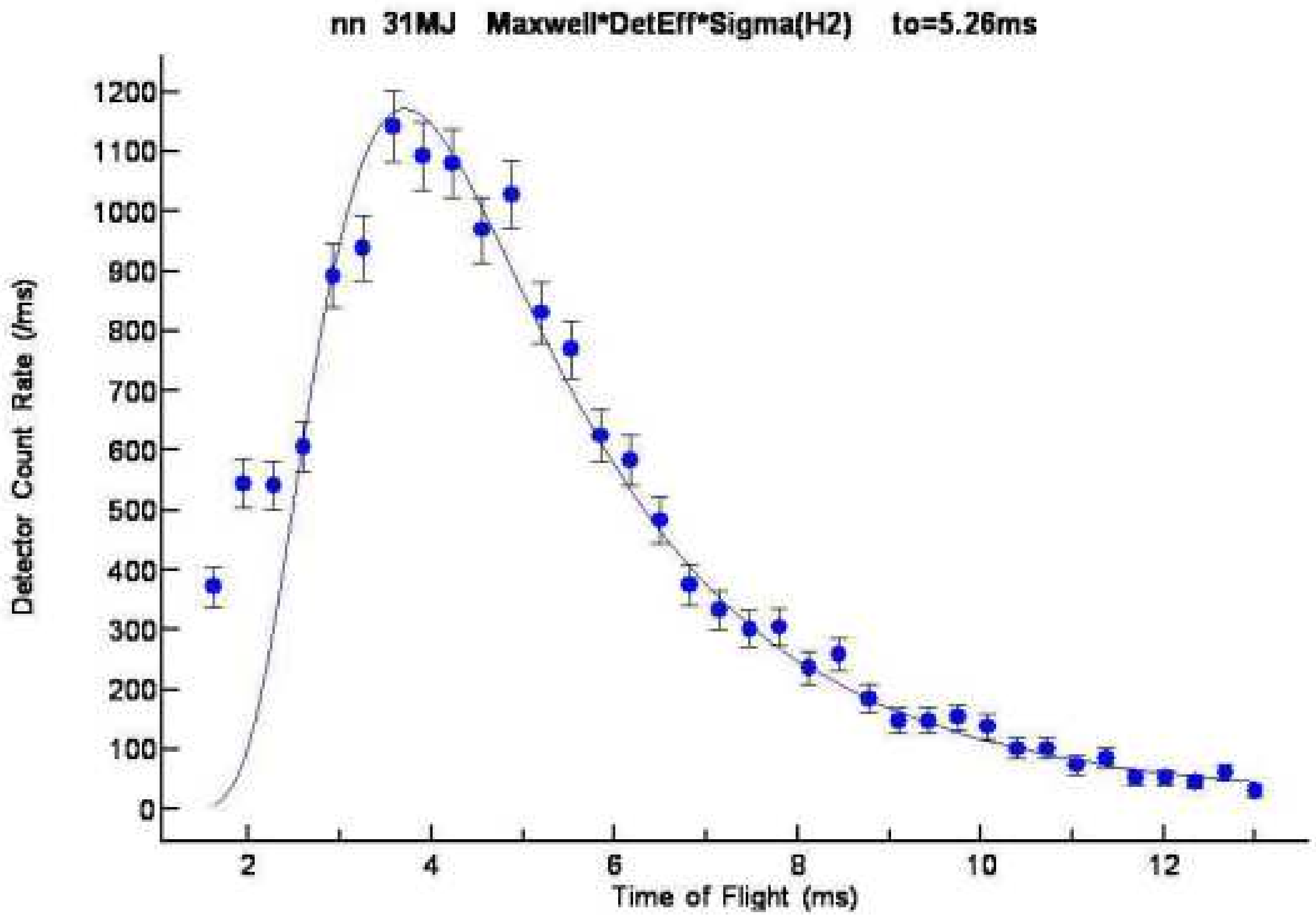


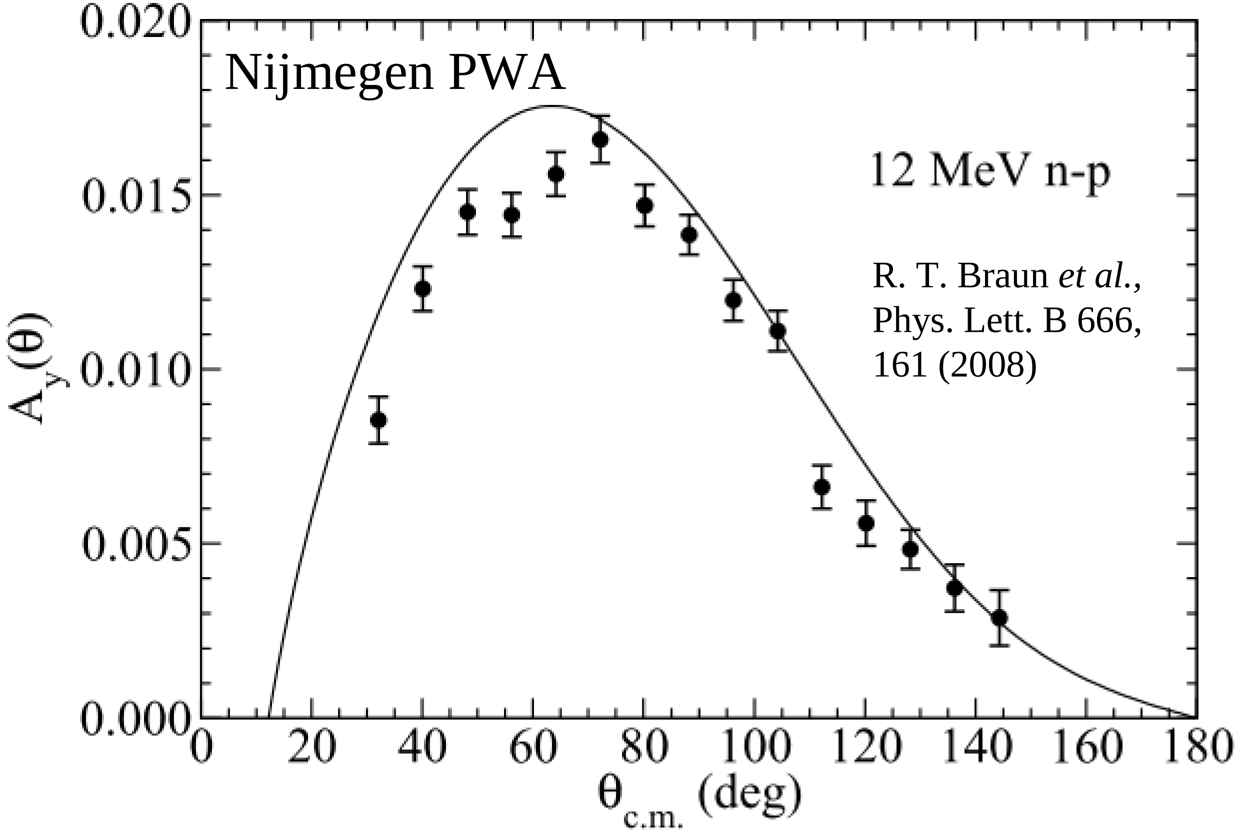
Figure 5: Neutron-neutron scattering data assuming desorption scattering from H_2 gas. The data points are identical to those in Figure 1 but the solid line fit is to a Maxwellian distribution, the appropriate detector efficiency and the scattering cross section of H_2.

A=2 Neutron-neutron scattering length a_{nn}

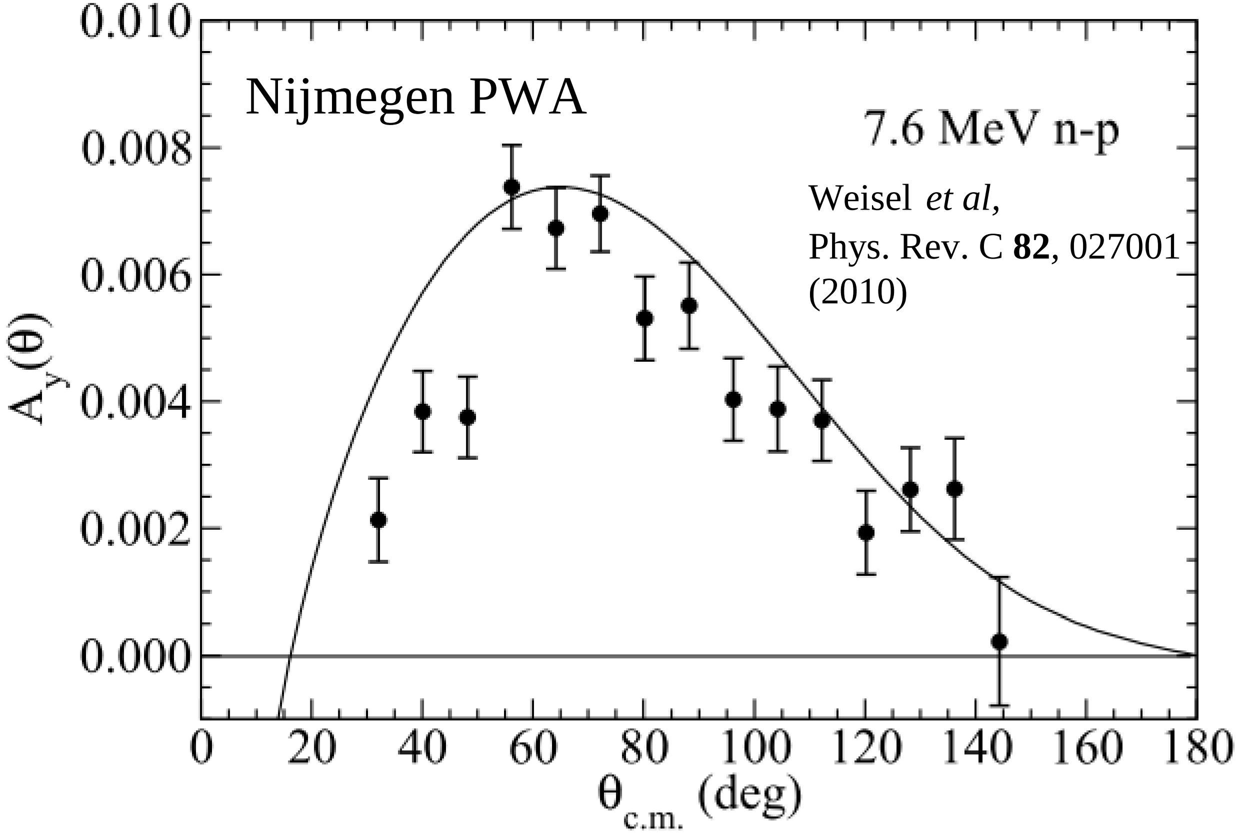
Direct n-n scattering experiment

Fix it ? Yes

A=2 Neutron-proton analyzing power $A_y(\theta)$



A=2 Neutron-proton analyzing power $A_y(\theta)$



A=2 Neutron-proton analyzing power $A_y(\theta)$

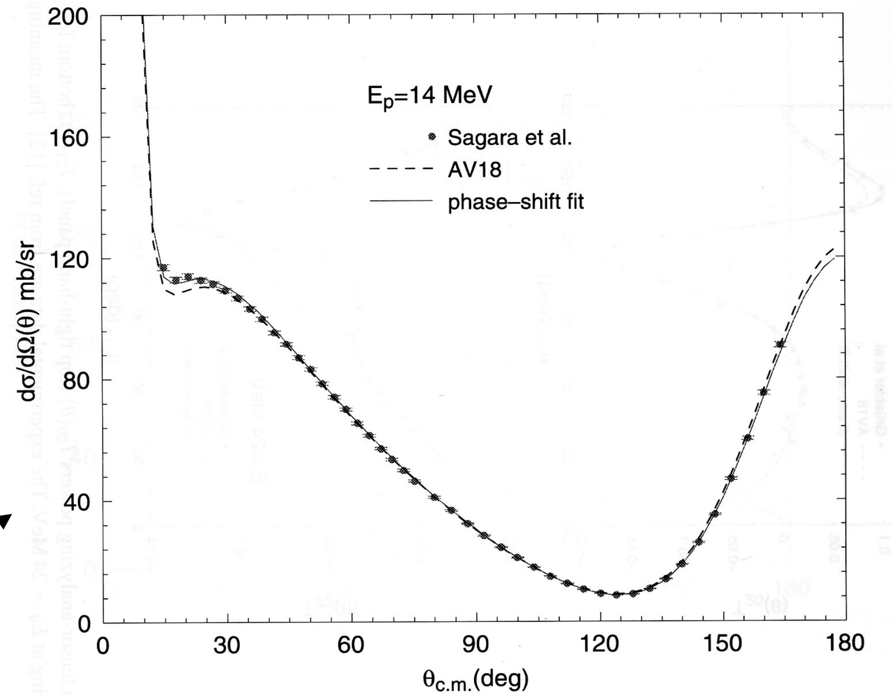
Real ? Yes

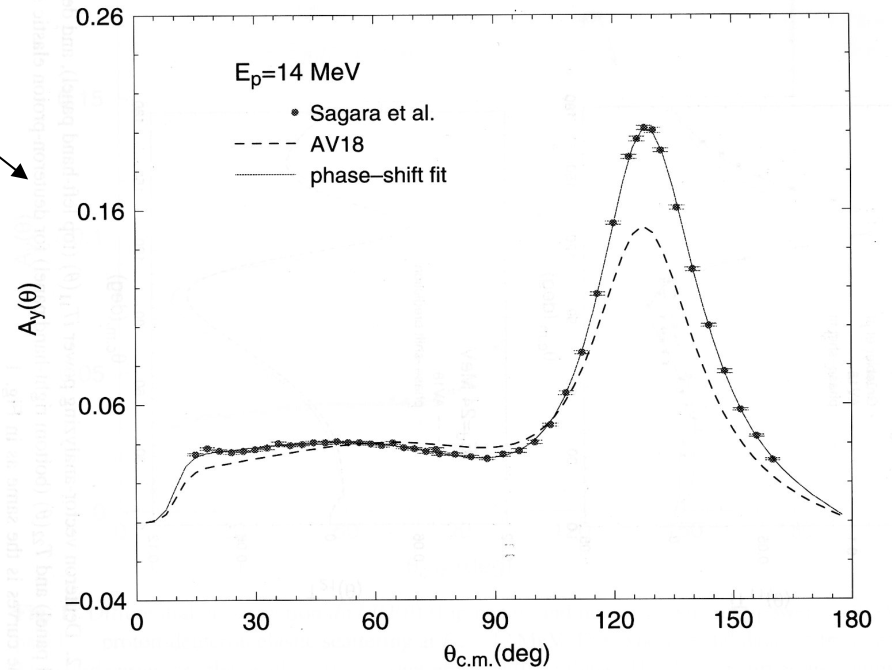
Relevant ? Yes, very much so

Fix it by performing new experiments? No
New measurements have no influence in new PWA analyses!
Fix it by modifying energy dependence of ^3P NN phase shifts at low energies? Requires new theoretical treatment of NN interaction.

$A=3$ Nucleon-deuteron elastic scattering

Proton-deuteron



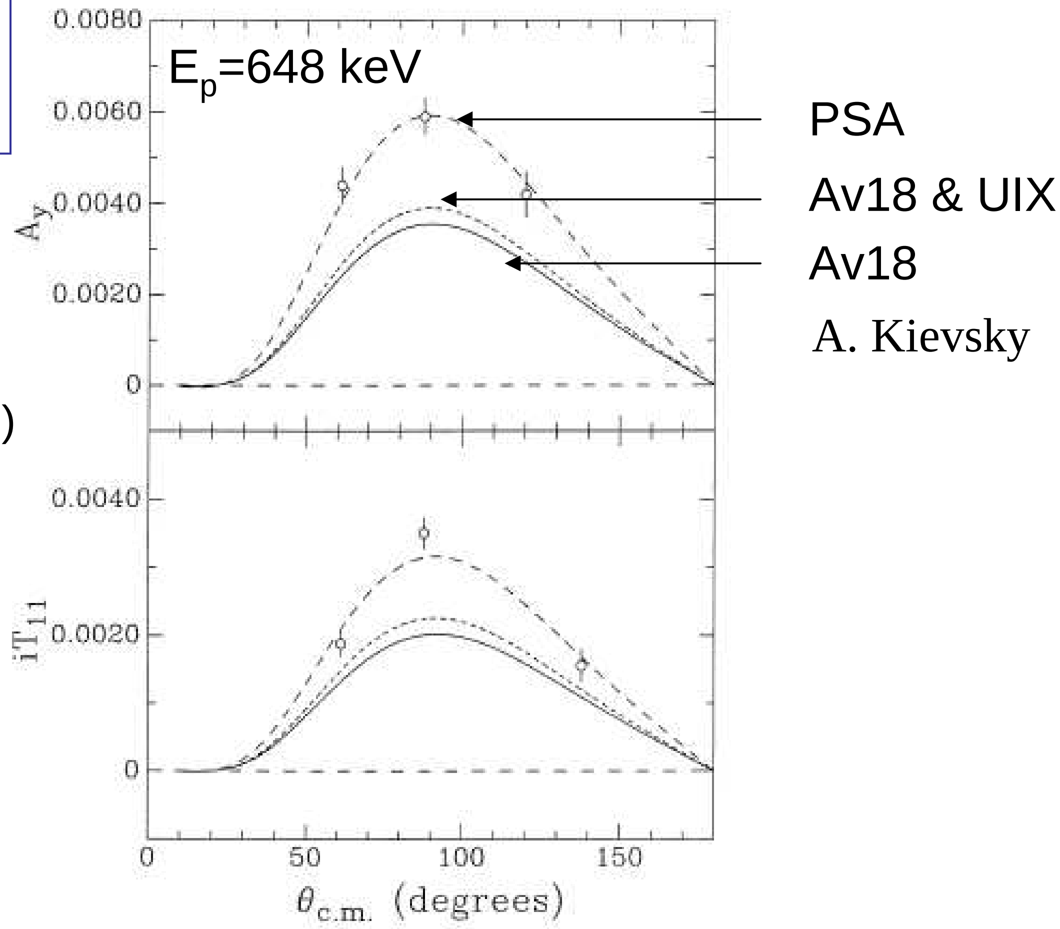


A_y puzzle

A=3
Nucleon-deuteron elastic scattering

C.R. Brune *et al*.
Phys. Lett. B **428**, 13 (1998)

TUNL

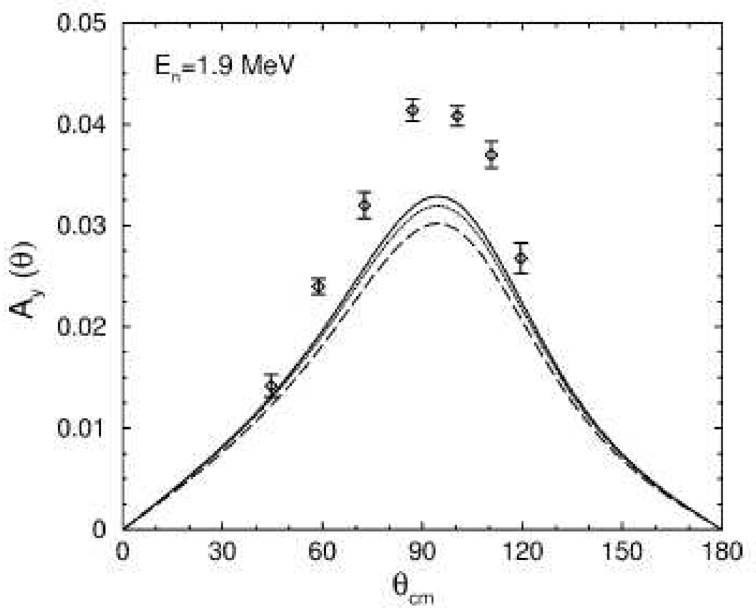


Proton-deuteron

A=3 Nucleon-deuteron elastic scattering

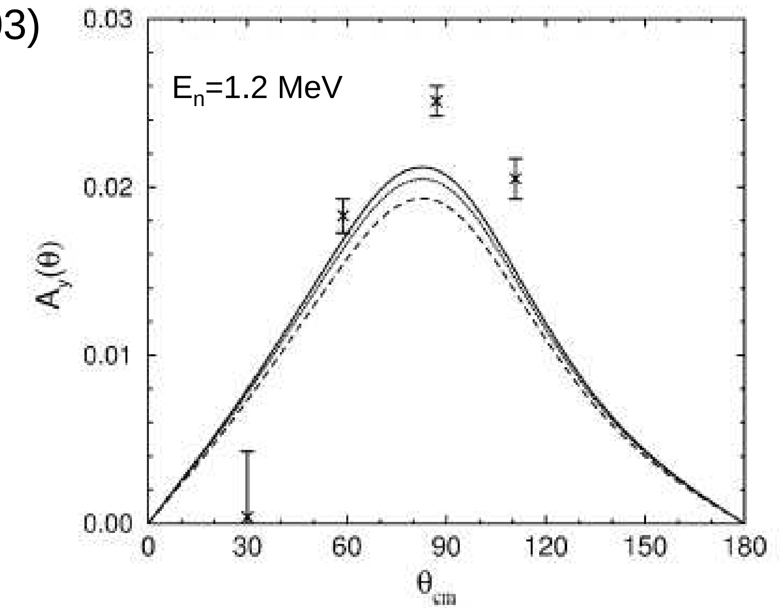
E. Neidel *et al*. Phys. Lett. B **552**, 29 (2003)

TUNL



CD-Bonn
Nijmegen
Av18

H. Witała

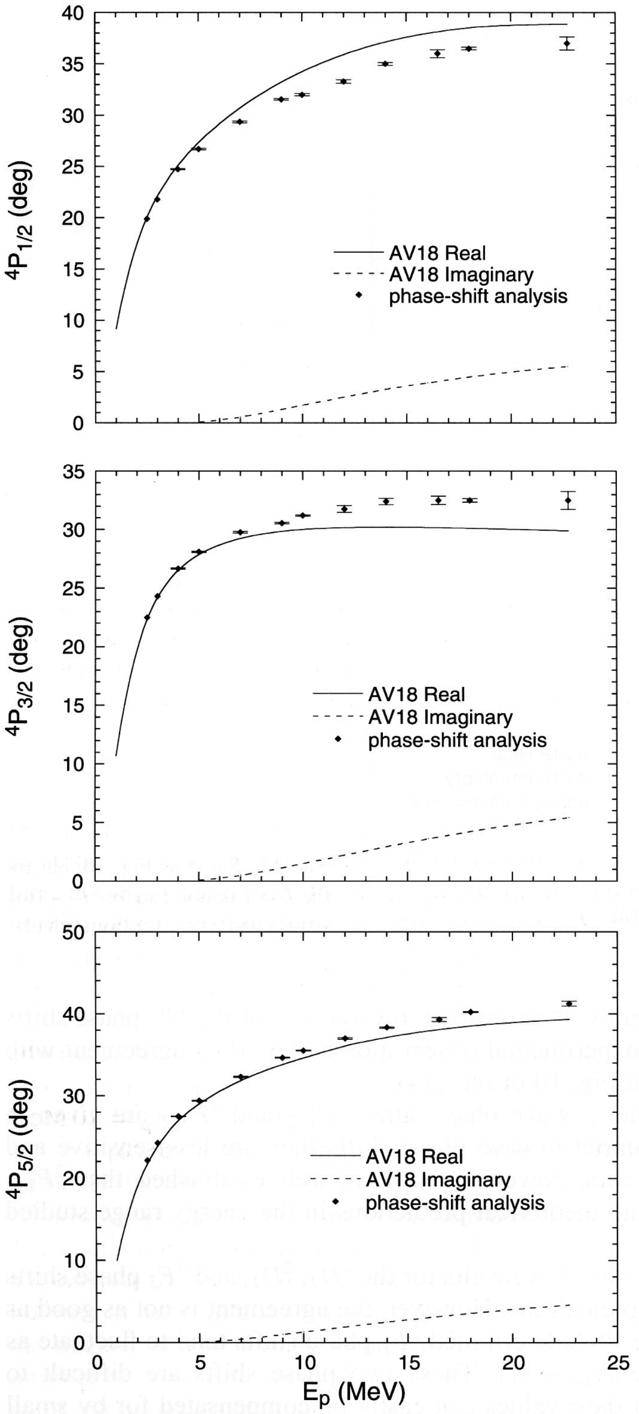


CD-Bonn
Nijmegen
Av18

Neutron-deuteron

A=3 Nucleon-deuteron elastic scattering

Proton-deuteron



PSA: Z. Chen *et al.*
Few-Body Syst. **35**, 15 (2004)
TUNL

A_y Puzzle

Real ? Yes

Relevant ? Not really

Fix it ? No, too hard! Supersensitive to $^3P_{0,1,2}$ NN interactions; most likely a NN problem, not a 3NF issue

A=3 Nucleon-deuteron breakup

W. von Witsch *et al*. (Bonn)

^{2}H(n,np)n np QFS

E_n=26 MeV

^{2}H(n,nn)p nn-QFS

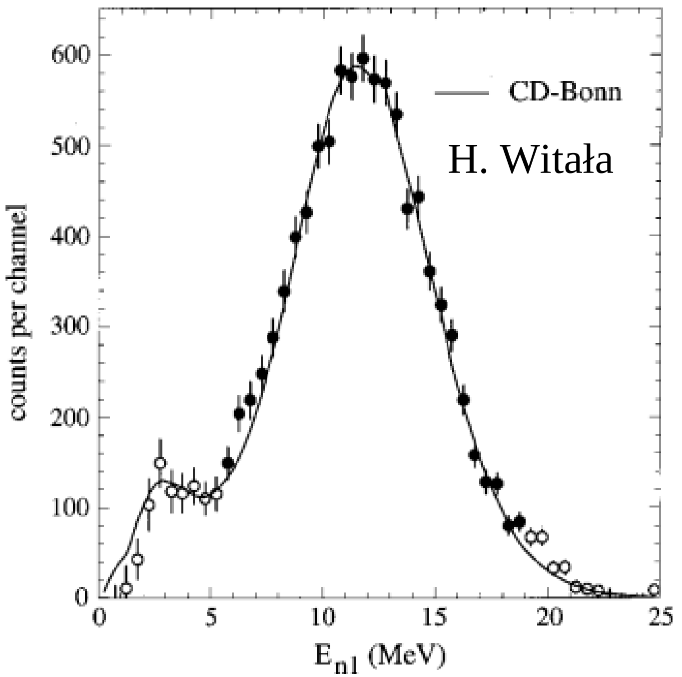


FIG. 2. Data for n-p QFS, projected onto the E_n axis. The solid line is the finite-geometry Monte Carlo prediction, using CD-Bonn for the N-N interaction.

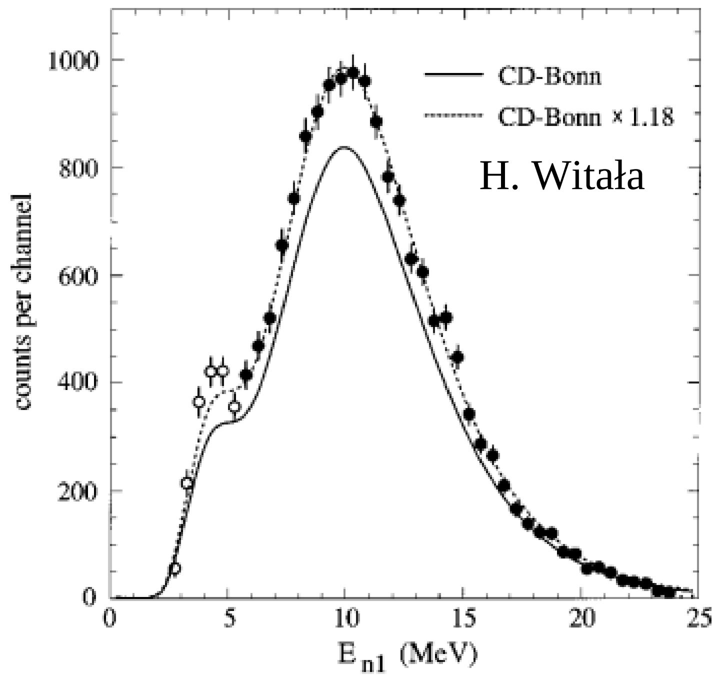


FIG. 4. HE data of Fig. 3, projected onto the E_{n1} axis. The solid curve represents the finite-geometry Monte Carlo prediction using CD-Bonn, the dotted line is the MC result normalized to the experiment by multiplication with a factor of 1.18. Only events with E_{n1} and E_{n2}>6 MeV have been included in the analysis.

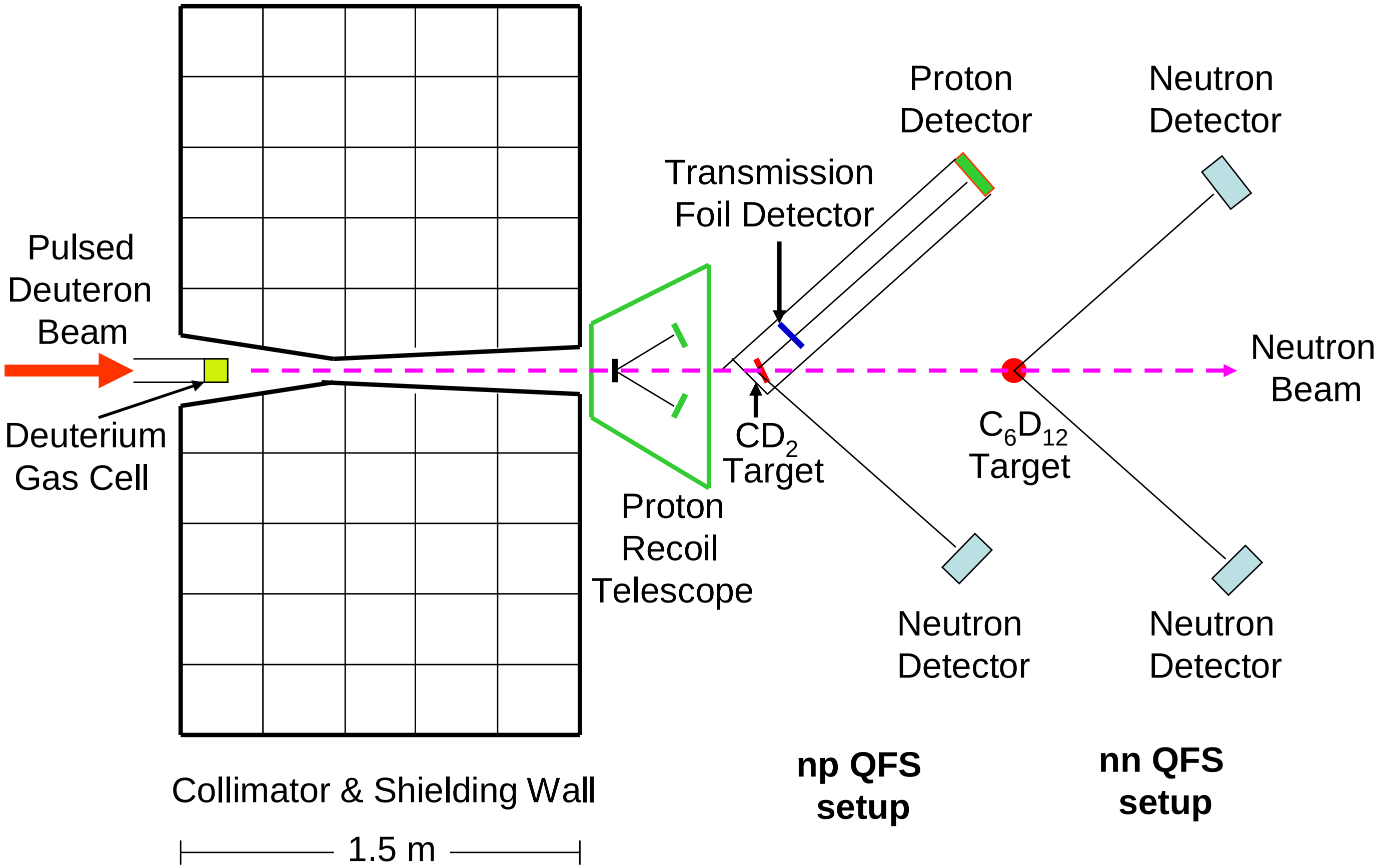
Real ? Not sure

Relevant? Yes

Fix it ? Yes

A=3 Nucleon-deuteron breakup

Proposed TUNL np and nn QFS experimental setup



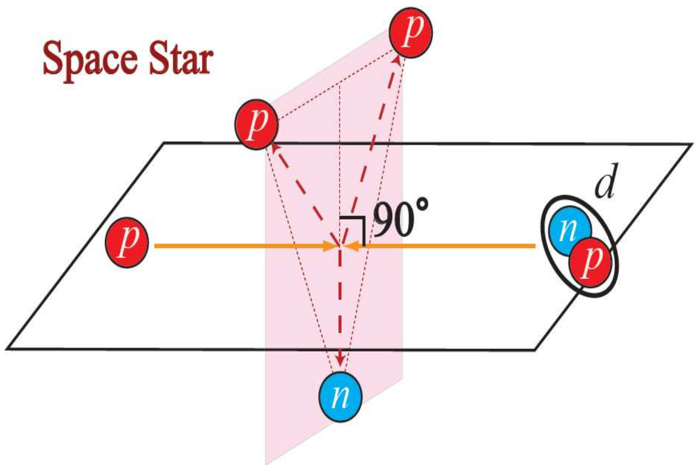
A=3 Nucleon-deuteron breakup

Space Star anomaly

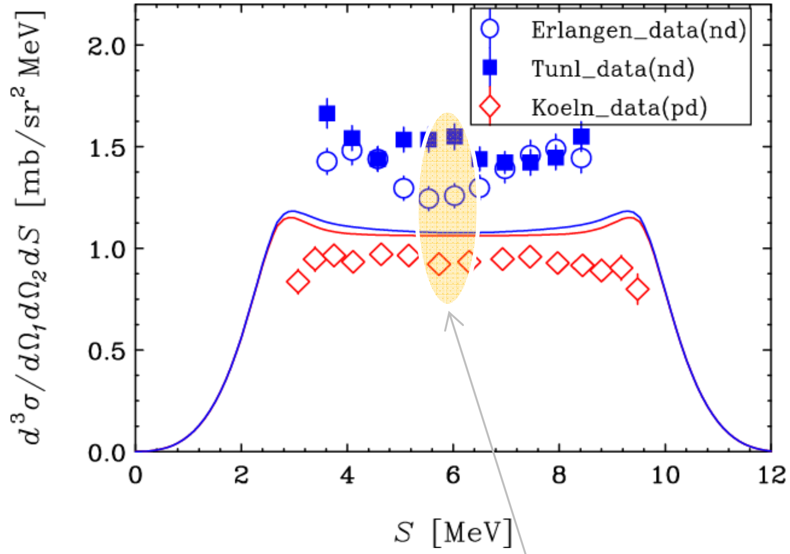
$n+d \to n+n+p$

$p+d \to p+p+n$

c.m. system



Space Star : Configuration in which the three outgoing nucleons form an equilateral triangle and they have the same momenta



Blue line : *nd calc*

Red Line : *pd calc*

Space Star Point

A. Deltuva

Calc : Coulomb effect is very small

nd : exp > calc

pd : exp < calc

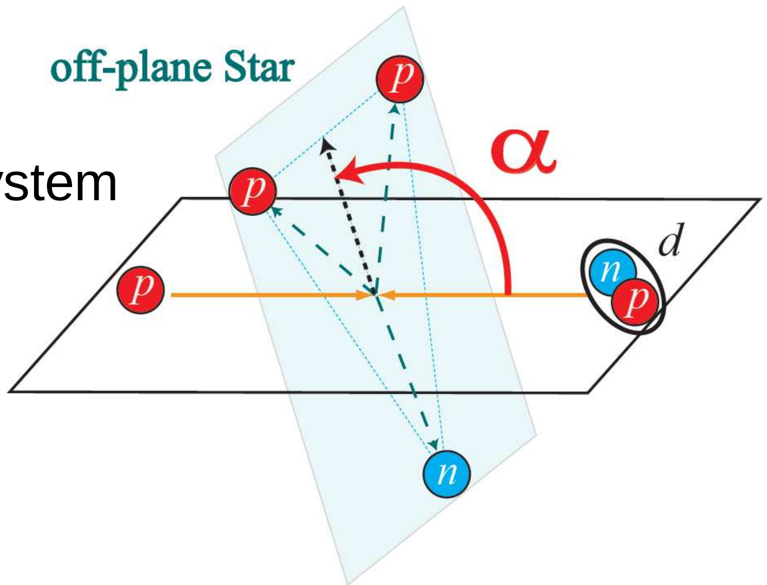
Depends on NN $^1S_0$ and $^3S_1$ forces only

K. Sagara

A=3 Nucleon-deuteron breakup

Off-Plane Space-Star anomaly

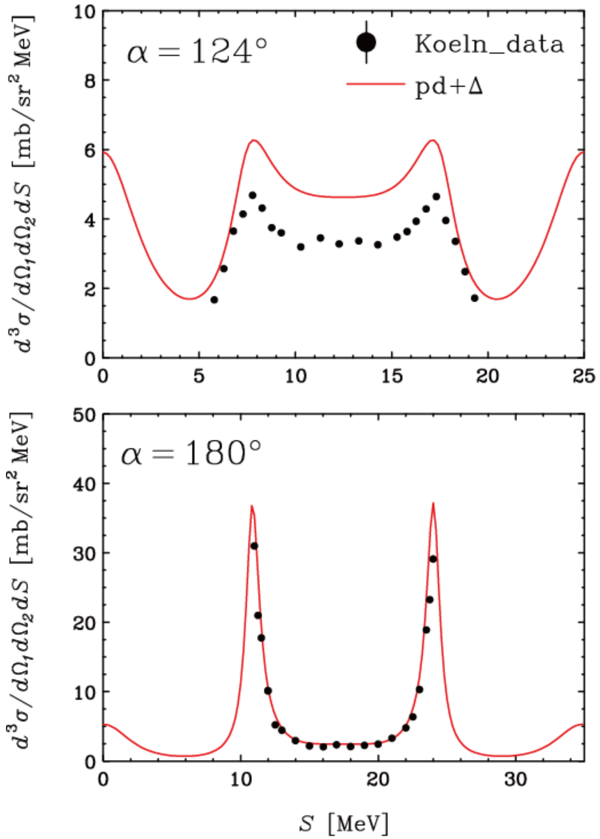
c.m. system



Define the angle between Space-Star plane and beam axis, α

$\alpha = 90°$ ⟹ Space Star

E_d=19 MeV

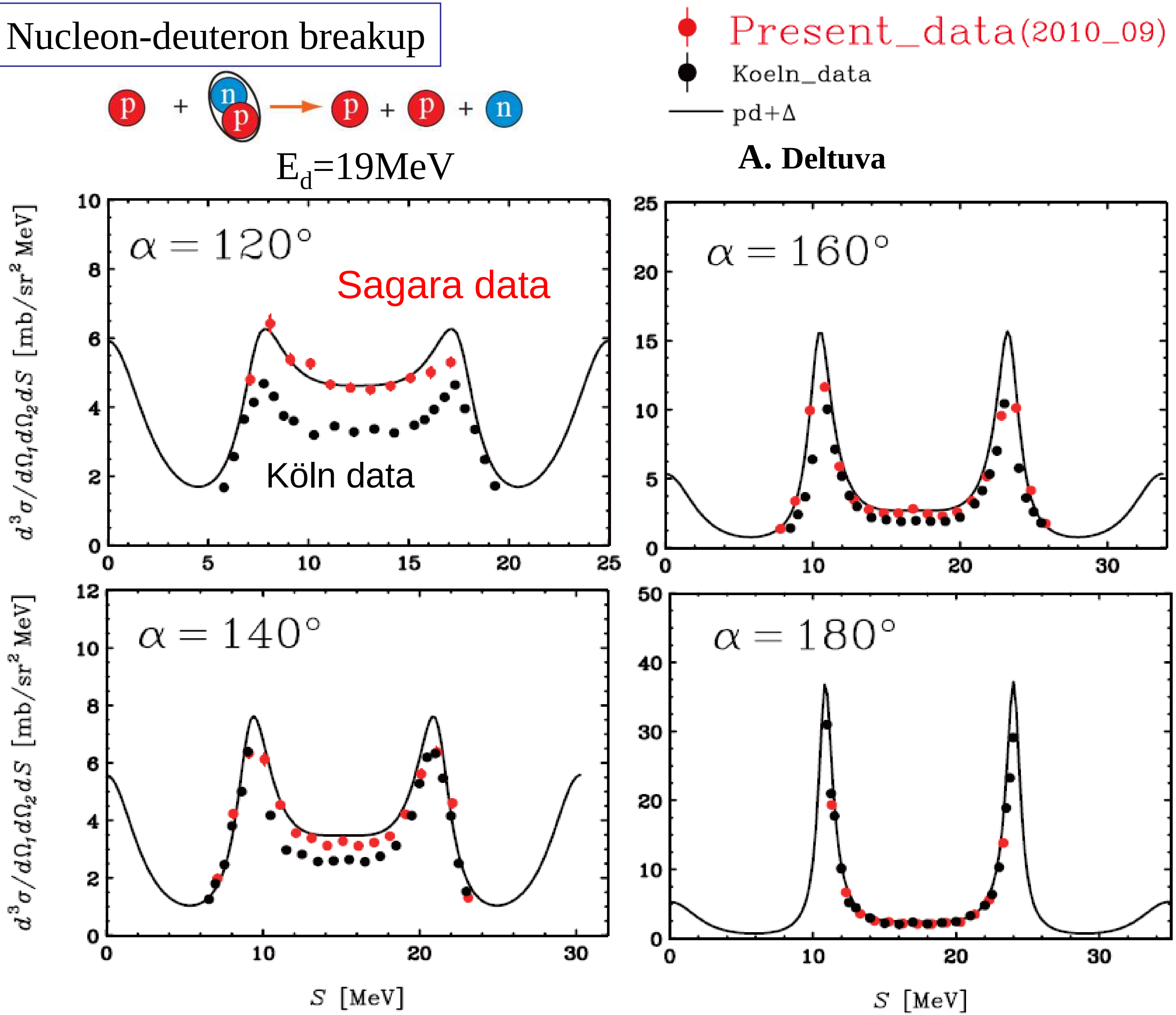


A. Deltuva

Cross section measured by Cologne group

K. Sagara

A=3 Nucleon-deuteron breakup



K. Sagara

A=3 Nucleon-deuteron breakup

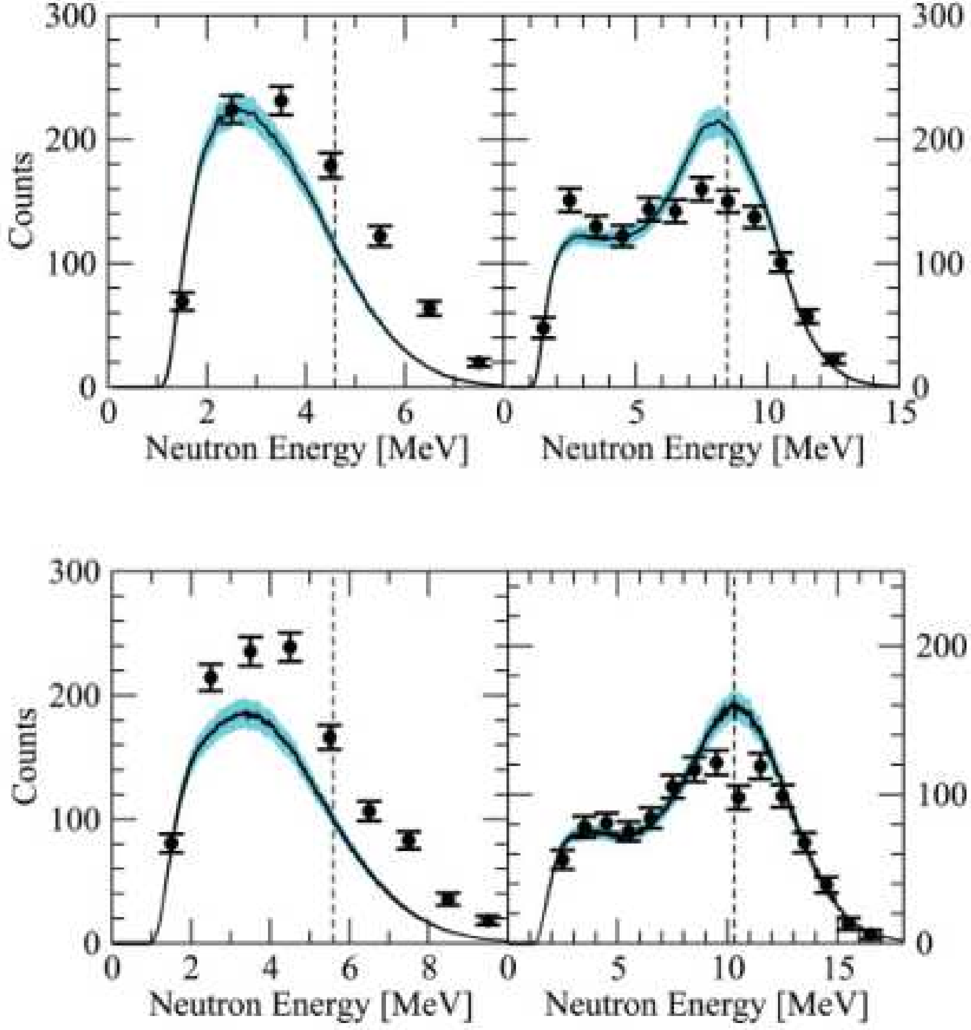
$^{2}H(n,np)n$

A.H. Couture *et al.*,
Phys. Rev. C **85**, 054004 (2012)

FIG. 2. (Color online) Three-dimensional renderings of top, front, and perspective views of experimental setup showing the target chamber (T), the charged particle arms (P), the SST (S) and CST (C) neutron detectors, and the neutron beam (red arrow). Please note that, in the front view, the neutron beam direction is out of the page.

A=3 Nucleon-deuteron breakup

α=90°   α=180°



E_n=16 MeV

H. Witała

^{2}H(n,np)n

E_n=19 MeV

Space-Star Anomaly

Real ? Yes

Relevant ? Yes

Fix it ? Yes!
Experimental and theoretical work is needed (3NFs).
Conjecture: n-n $^1S_0$ problem?

A=4 Nucleon-^{3}He elastic scattering

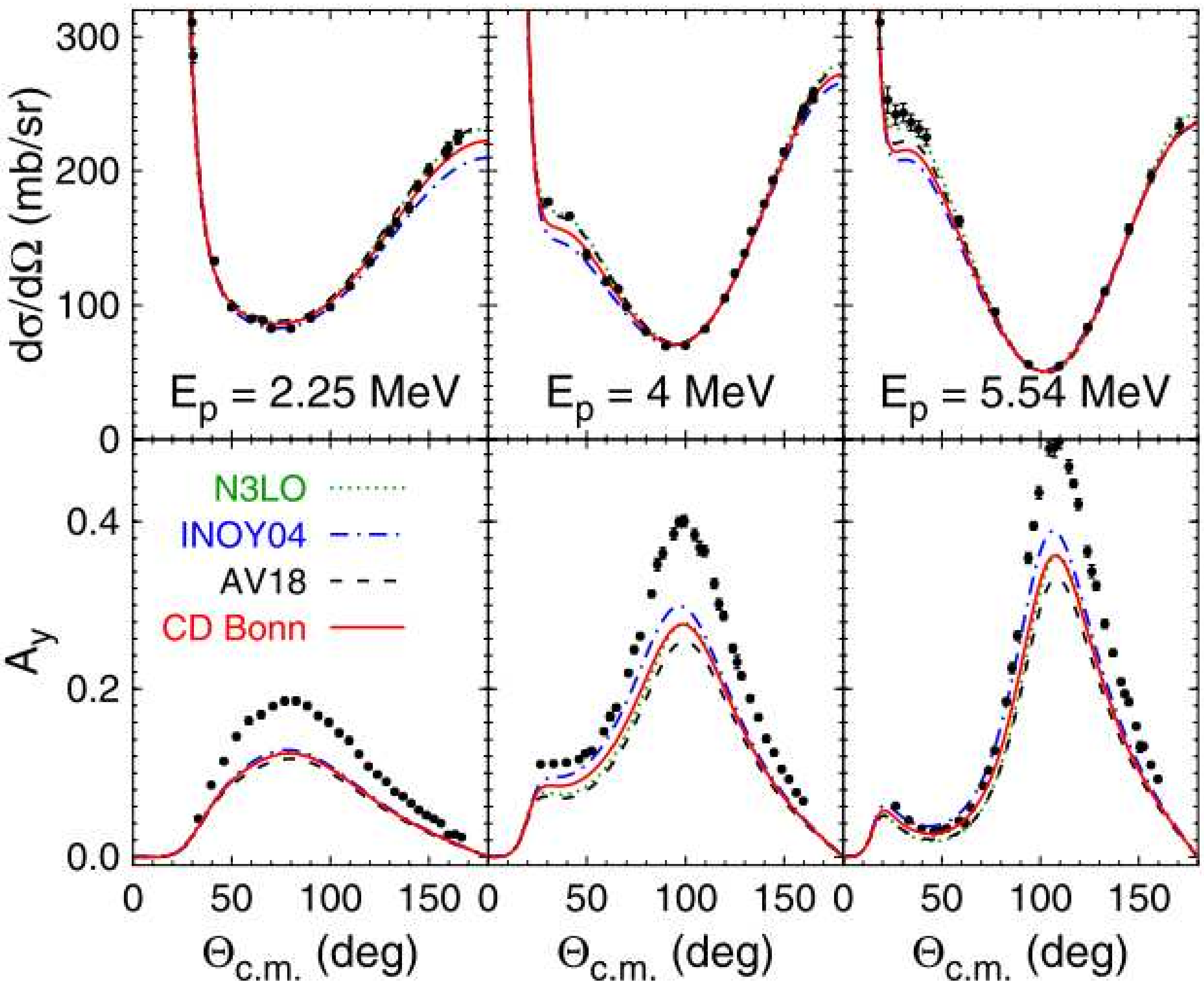
Four-Nucleon Elastic Scattering

p - ^{3}He	T=1
n - ^{3}H	T=1
p - ^{3}H	T=0,1
n - ^{3}He	T=0,1

A=4 Nucleon-^{3}He elastic scattering

p – ^{3}He

Fisher 2006



McDonald 1964

Alley 1993

A. Deltuva

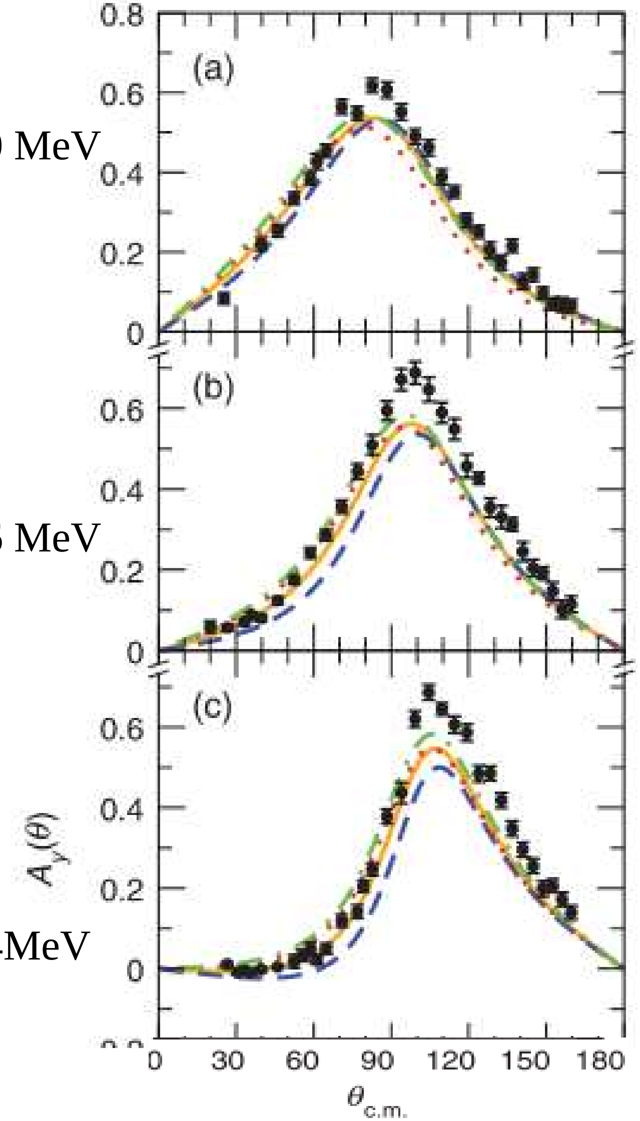
A=4 Nucleon-^{3}He elastic scattering

n - ^{3}He

E_n=1.60 MeV

E_n=2.26 MeV

E_n=3.14MeV



J. Esterline *et al*., PRL **110**,152503 (2013)

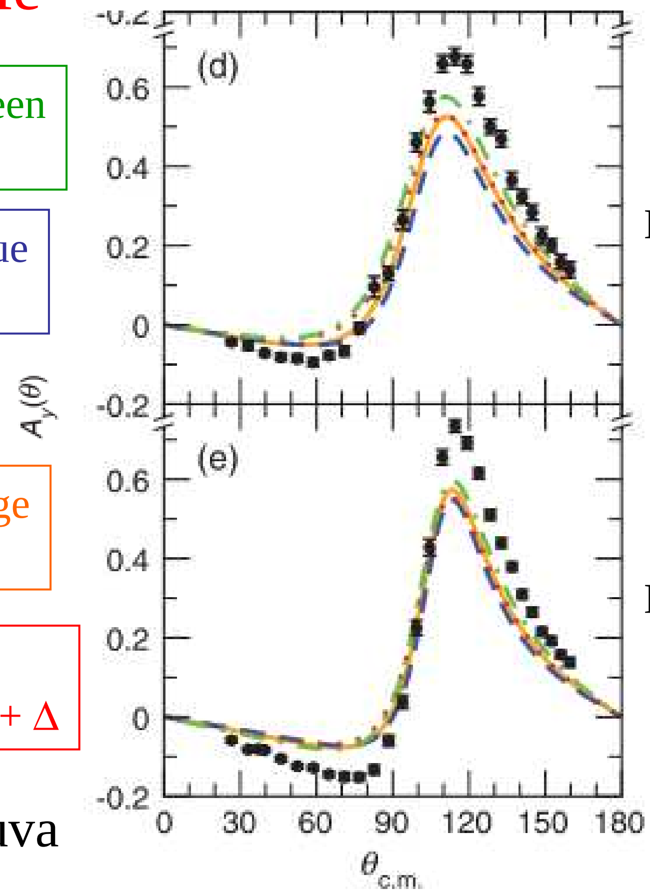
dashed green
INOY04

dashed blue
AV18

solid orange
CD Bonn

dotted red
CD Bonn + Δ

A. Deltuva



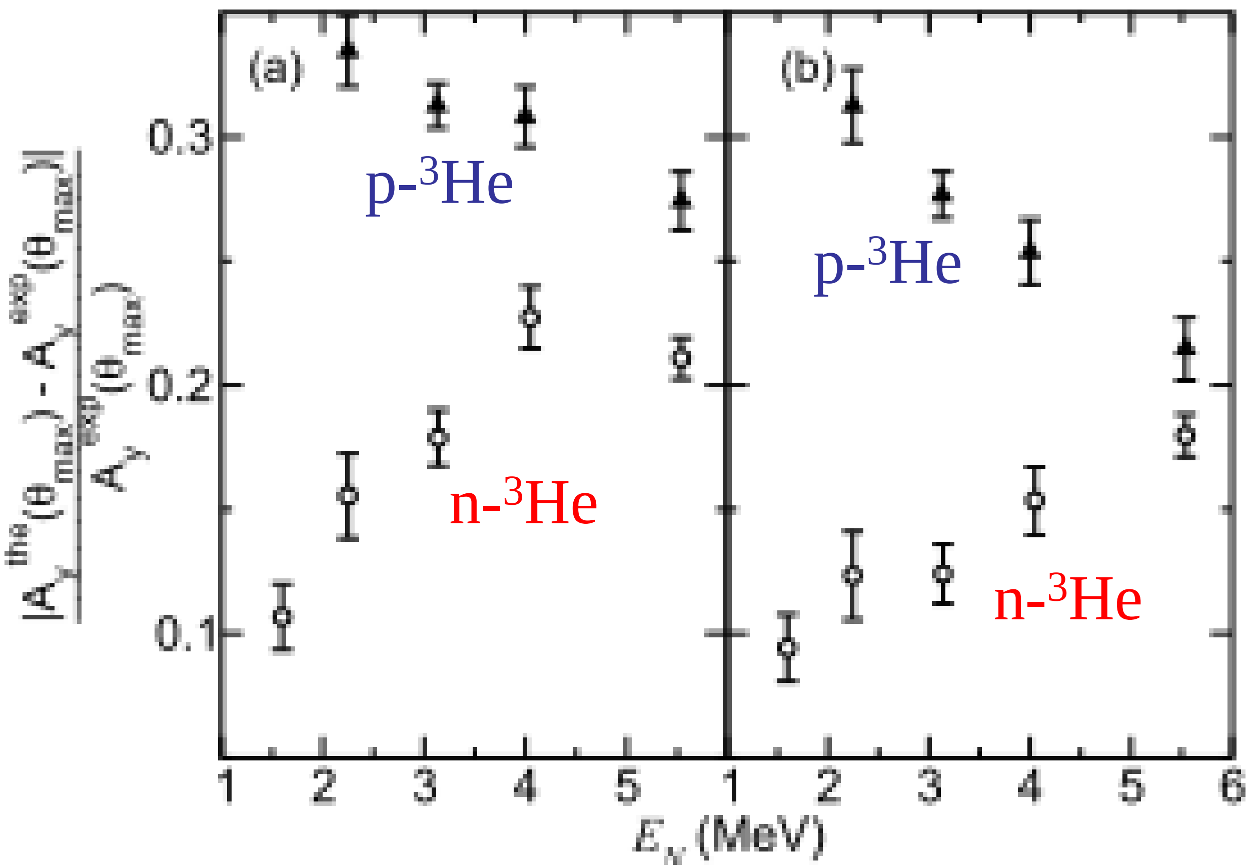
E_n=4.05 MeV

E_n=5.54 MeV

FIG. 3 (color). Measured and calculated values of the $\vec{n}$-^{3}He analyzing power $A_y(\theta)$ at neutron energies of (a) 1.60, (b) 2.26, (c) 3.14, (d) 4.05, and (e) 5.54 MeV. Theoretical predictions using the AV18 [19], INOY04 [20], CD Bonn [21], and CD Bonn + Δ [22] potentials are shown in dashed blue, dash-dotted green, solid orange, and dotted red curves, respectively; experi-

A=4 Nucleon-^{3}He elastic scattering

CD Bonn, 7.26 MeV INOY04, 7.73 MeV



A=4 Nucleon-^{3}He elastic scattering

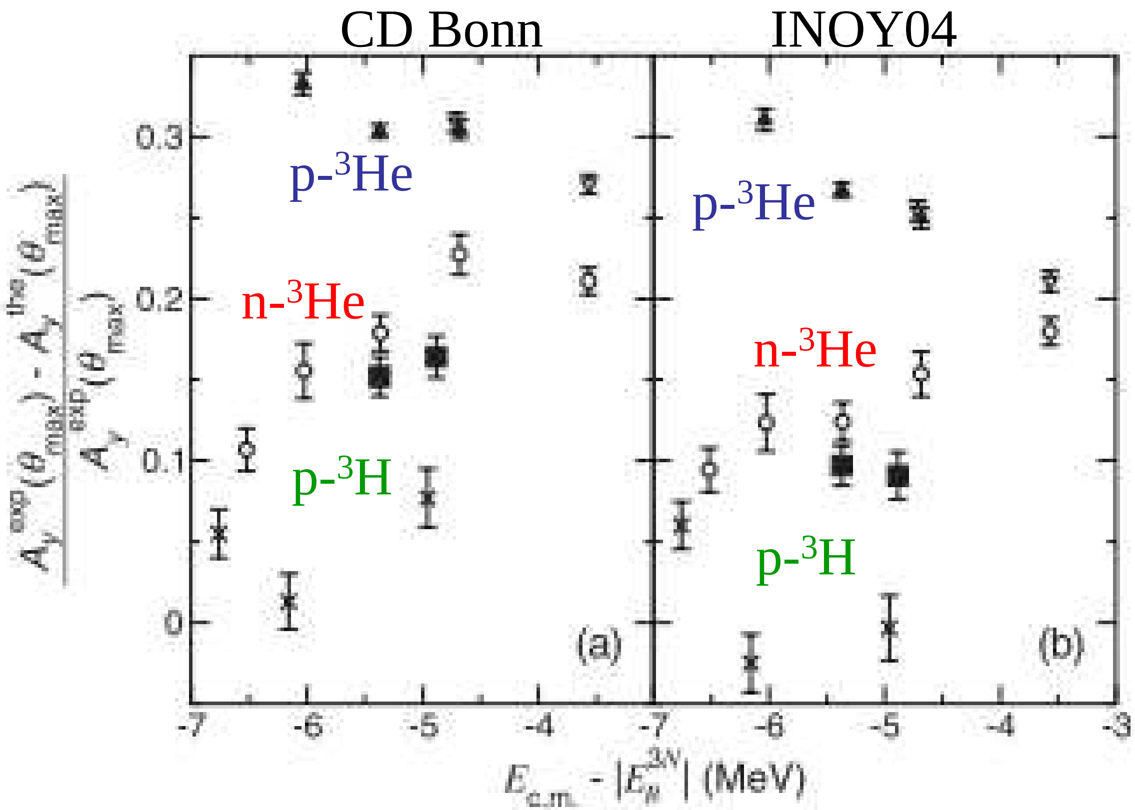


FIG. 4. A_y relative difference between measurement and calculations using (a) CD Bonn or (b) INOY04 NN potentials. The total energy with respect to the four-free-nucleon threshold, given by the center-of-mass energy minus the three-nucleon bound state binding energy E_B^{3N}, provides an accurate comparison between different systems. As organized by publication, data for $\vec{p}$-^{3}He are represented by triangles filled [4] and unfilled [5], those for $\vec{p}$-^{3}H by solid squares [23] and crosses [24], and $\vec{n}$-^{3}He by open circles (the present measurements). We note the excellent agreement between [4,5] near -4.7 MeV resulting in an overlap.

A=4 Nucleon-^{3}He elastic scattering

Difference between relative difference for p-^{3}He and n-^{3}He $A_y(\theta)$ at maximum

Real ? Yes

Relevant ? Yes

Fix it ? Yes. Try to understand isospin dependence.
New p-^{3}H data are needed (T=0,1).
n-^{3}H data are needed (T=1).

Conclusion

Currently, there are too many unsolved problems in few-nucleon physics.

Let’s keep working on them.