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

$^2\text{H}(\pi^-,\gamma\text{n})\text{n}$ at LAMPF  

\[ a_{nn} = -18.5 \pm 0.4 \text{ fm (stat)} \pm 0.3 \text{ (syst)} \]


$^2\text{H}(\text{n},\text{nn})\text{p}$ at TUNL  

\[ a_{nn} = -18.7 \pm 0.6 \text{ fm} \]


But W. von Witsch got consistently smaller values using

$^2\text{H}(\text{n},\text{np})\text{n}$ at Bonn  

\[ a_{nn} = -16.1 \pm 0.4 \text{ fm and } -16.3 \pm 0.4 \text{ fm} \]


Real? Yes

Relevant? Probably not

Fix it? Maybe
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

![Diagram of recoil setup]

$E_n = 25.3$ 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

$E_{n0} = 19$ MeV
$\theta_n = 51.7^\circ$ and $\theta_p = 45.0^\circ$, $\phi_{np} = 180^\circ$
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 $\sim 10^{18}/\text{cm}^2\text{s}$, 1000 $\mu$s pulse

Project funded by the International Science and Technology Center (ISTC)
$A=2$ Neutron-neutron Scattering length $a_{nn}$

YAGUAR Reactor
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 !!!


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 $\text{H}_2$. 
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.
Figure 5: Neutron-neutron scattering data assuming desorption scattering from H₂ 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 H₂.
Direct n-n scattering experiment
A=2 Neutron-proton analyzing power \( A_y(\theta) \)
$A=2$ Neutron-proton analyzing power $A_y(\theta)$

Nijmegen PWA

7.6 MeV n-p

Weisel et al,
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.
TUNL

Proton-deuteron elastic scattering

\[ E_p = 648 \text{ keV} \]

PSA
Av18 & UIX
Av18
A. Kievsky
$A=3$
Nucleon-deuteron elastic scattering

TUNL

H. Witała

CD-Bonn Nijmegen Av18

CD-Bonn Nijmegen Av18

Neutron-deuteron
A=3 Nucleon-deuteron elastic scattering

Proton-deuteron

PSA: Z. Chen et al.
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)

\[ ^2H(n,np)n \quad np \text{ QFS} \quad E_n=26 \text{ MeV} \quad ^2H(n,nn)p \quad nn-QFS \]

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 \( E_{n2} \geq 6 \text{ MeV} \) 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**

\[ n+d \rightarrow n+n+p \]
\[ p+d \rightarrow p+p+n \]

C.m. system

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

**Calc:** Coulomb effect is very small

\[ nd : \text{exp} > \text{calc} \]
\[ pd : \text{exp} < \text{calc} \]

Depends on NN \(^1S_0\) and \(^3S_1\) forces only

K. Sagara
A=3 Nucleon-deuteron breakup

Off-Plane Space-Star anomaly

Define the angle between Space-Star plane and beam axis, $\alpha$

$\alpha = 90^\circ \rightarrow \text{Space Star}$

$E_d = 19 \text{ MeV}$

K. Sagara

A. Deltuva

Cross section measured by Cologne group
A=3 Nucleon-deuteron breakup

\[ E_d = 19 \text{MeV} \]

\[ \alpha = 120^\circ \]

Sagara data

Köln data

\[ \alpha = 160^\circ \]

\[ \alpha = 140^\circ \]

\[ \alpha = 180^\circ \]

K. Sagara
$^2\text{H}(n, np)n$

A.H. Couture et al.,

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.
$^{2}\text{H}(n,\text{np})\text{n}$

$E_n = 16 \text{ MeV}$

$E_n = 19 \text{ MeV}$

$\alpha = 90^\circ$

$\alpha = 180^\circ$

H. Witała
Space-Star Anomaly

Real ? Yes

Relevant ? Yes

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

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

Four-Nucleon Elastic Scattering

- $p - ^3\text{He}$ $T=1$
- $n - ^3\text{H}$ $T=1$
- $p - ^3\text{H}$ $T=0,1$
- $n - ^3\text{He}$ $T=0,1$
$A=4$ Nucleon-$^3$He elastic scattering

$p - ^3$He

\[ \frac{d\sigma}{d\Omega} \text{ (mb/sr)} \]

$E_p = 2.25 \text{ MeV}$  
$E_p = 4 \text{ MeV}$  
$E_p = 5.54 \text{ MeV}$

$A_Y$  

$\Theta_{\text{c.m.}}$ (deg)

Fisher 2006

McDonald 1964

Alley 1993

A. Deltuva
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 + $\Delta$ [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 $E_{3N}$, provides an accurate comparison between different systems. As organized by publication, data for $\bar{p}$-$^3$He are represented by triangles filled [4] and unfilled [5], those for $\bar{p}$-$^3$H by solid squares [23] and crosses [24], and $\bar{n}$-$^3$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.