When Three's a Crowd
Konrad Aniol

• Who? Sophia Iqbal's thesis
• What? Structure of $^4$He nucleus
• Where? Thomas Jefferson National Accelerator Facility
• Why? Creation of the chemical elements
• Cast of characters in this story?
  • Fermions
  • Bosons
Probing for high momentum protons in $^4$He via the $^4$He(e,e'p)$^3$H reaction

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at Jefferson Lab

Nathaniel See
at Yorktown
Jefferson Lab, Newport News, VA

Multi billion electron volts accelerator
Quantum Mechanics Sociology

Fermions

Bosons

<table>
<thead>
<tr>
<th>Impatient</th>
<th>Easygoing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short tempered</td>
<td>Social</td>
</tr>
<tr>
<td>Competitive</td>
<td>Procrastinatorator</td>
</tr>
<tr>
<td>Ambitious</td>
<td>Creative</td>
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</tbody>
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Type A

Type B

Personality

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Life with the Fermions
Keep out of my space dude!
Life with the Bosons
Group Hug!
How to Build a Community?
There must be at least a two body interaction
Sometimes Three's a Crowd!
Sometimes 3 makes a stronger community

Hand Shaking helps build a community
How can Fermions form a nucleus?

Bosons mediate hand shaking between fermions

Image By Marekich - Own work (vector version of PNG image), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=21701588
In $^4$He there are 2 protons and 2 neutrons.
Can $^{4}\text{He}$ be configured as $^{3}\text{H} + \text{p}$?
In Sophia's experiment a high energy electron knocks out a proton.
In Sophia's experiment a high energy electron knocks out a proton

$^2\text{H} + n \rightarrow P_n$

vertex

e

e'

virtual photon

1

2

3

4

Pd

Pp
In Sophia's experiment a high energy electron knocks out a proton

\[ p + n + n + X \]?
In Sophia's experiment a high energy electron knocks out a proton

\[ p + n + n + X \]?

The virtual photon is more like a cruise missile for the \(^4\)He target.
How to study automobile structure

How much identifiable structure would you expect to find in the debris?
Use conservation of energy and momentum.

\[ E_i = \text{mass of } ^4\text{He} + \text{energy of electron} \]

\[ P_i = \text{momentum of incoming electron} \]

Measure momentum of scattered electron, \( P_e' \)

Measure momentum of knocked out proton, \( P_p \)

Measured final state energies \( E_{fe} + E_{fp} \)

\[ P_f = P_e' + P_p + P_x, \text{ } P_x \text{ is the missing momentum of the debris} \]

\[ E_{\text{miss}} = E_i - (E_{fe} + E_{fp}) \]

Plot missing energy, \( E_{\text{miss}} \)

From the shape of \( E_{\text{miss}} \) plot we can identify certain final states
Magnetic spectrometers are essential for measuring high momentum particles.
Calculated $^4$He SRC target properties in electron beam

Figure 2: Example of a CFD calculation for the SRC target geometry. The beam enters from the left and the cryofluid enters and exits at the flanges at the left. There is no exit for the cryofluid at the right end of the aluminum can. Calculation and image provided by Silviu Covrig [1].

Computational Fluid Dynamics Calculation
Count rate along the 20cm long SRC target for 3 beam currents

Aluminum Can Windows

Up stream

Down stream

Black curve = 4 uA
Blue curve = 47 uA
Red curve = 60 uA

20K cryogenic
Cooling only at beam entrance

The count along the position in the target is affected by the local density and by the cross section which is strongly forward peaked. We need to isolate the cross section effects from the local density effect.

Figure 3: Normalized counts per Coulomb (vertical axis) along the beam’s path for 4 different beam currents, 4μA (black), 47μA (blue), 60μA (red). The horizontal axis is along z in meters. The aluminum end caps are seen as sharp spikes at ±0.1 m.
Comparing high current count rates to low current count rates

The ratio of $\text{cnts(I)}/\text{cnts(4uA)}$ should remove much of the cross section angular dependence.

There may still be local density effects because the hydrodynamics of the fluid may not scale linearly with beam current.
Beam current calculated fluid dynamic effects on gas density

CFD calculations predict complicated density fluctuations for the SRC target.

Figure 6: Prediction of the changing target density along the beam path for three beam currents, $4\mu A$ (blue), $47\mu A$ (red), $60\mu A$ (green).

Predicted density versus target location from Computational Fluid Dynamics
Pm = 0.353 GeV/c

Pmiss = 0.575 (GeV/c)

Pmiss = 0.353 (GeV/c)

Pmiss = 0.632 (GeV/c)
The data at high missing momentum disagree with theory by a factor of 10!

Is this a sign of three body interactions favoring a 3 nucleon final configuration?
Three body forces in nuclei provide more binding than two body forces alone.

Models 3-body forces based on pion exchange.

<table>
<thead>
<tr>
<th>TABLE II. Experimental and GFMC energies (in MeV) of particle-stable or narrow-width nuclear states and of neutron drops. Monte Carlo statistical errors in the last digits are shown in parentheses. The final column gives experimental widths in keV.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AV8</strong></td>
</tr>
<tr>
<td>3H(1/2+)</td>
</tr>
<tr>
<td>3He(1/2+)</td>
</tr>
<tr>
<td>4He(0+)</td>
</tr>
<tr>
<td>6He(0+)</td>
</tr>
</tbody>
</table>

The need for 3-body interactions in ground state and excited nuclear states is well established. A wide range of models can fit these binding energies. The Iqbal experiment suggests another experimental observable is available for 3NN interactions.

We propose that a serious investigation of the shape of the Emiss spectrum in the 3 body region from proton knockout in $^4$He may constrain the range of possible 3NN interaction models.
After many decades studying various P+P and N+P reactions it is well established that 2body interactions are insufficient to calculate nuclear structure.
Stars produce the elements
That's why we want to know if three's a crowd.

Nucleosynthesis of the elements depends on how neutrons and protons interact
Unstable nuclei are important ingredients in nucleosynthesis.