Nuclear Forces at Short Distances and Superdense Nuclear Matter

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October 31, 2013 Texas A&M University-Commerce
Florida International University

In Miami
One of Largest Public Research University  52,000
Nuclear Group & Jefferson Lab & 21st in producing PhD in Nuclear Physics
Nuclear Forces at Short Distances

- **Theory:**
  - QCD in NN Systems, High Energy Approximations
  - Relativistic Bound State Problem

- **Methodology**
  - Hard Nuclear Processes

- **Experimentation**
  - JLab, BNL, FAIR, JPARC
Two New Properties of High Momentum Component of Momentum Distributions in Asymmetric Nuclei

Protons are more Energetic in Neutron Rich High Density Nuclear Matter

Universal Property of Asymmetric Two Component Fermi Systems
Superdense Matter $10^9 \text{ ton/cm}^3$
On July 4, 1054 A.D., Chinese astronomers noticed a "guest star" in the constellation Taurus; this star became about 4 times brighter than Venus in its brightest light and was visible in daylight for 23 days.

“I bow low. I have observed the apparition of a guest star. Its color was an iridescent yellow... The land will know great prosperity”

Yang Wei-T, Imperial Astronomer of Sung Dynasty
Sung dynasty chronicles of the appearance of the Crab Nebula Supernova of 1054 AD.

From the Sung-shih [Annals, of the Sung Dynasty] (Astronomical Treatise, chapter 56).

"On the 1st year of the Chi-ho reign period, 5th month, chi-chou (day) [July 4, 1054], a guest star appeared approximately several inches to the south-east of Tian-kuan [Aldebaran]. After a year and more it gradually vanished."

From the Sung-shih (Chapter 9).

"On the first year of the Chia-wu reign period, 3rd month, xin-wei (day). The Director of the Astronomical Bureau reported that since the 5th month of the 1st year of the Chih-ho reign period, a guest star had appeared in the morning at the east, guarding Tian-kuan, and now [two years after its first appearance] it has vanished."

From the Sung-hui-yao [Essentials of the Sung dynasty history] (Chapter 52)

"On the 1st year of the Chih-ho reign period, 7th month, 22nd day [August 27, 1054] ... Yang Wei-te said 'I humbly observe that a guest star has appeared. Above the star in question there is a faint glow, yellow in colour. If one carefully examines the prognostications concerning the emperor, the interpretation is as follows: The fact that the guest star does not trespass against Pi and its brightness is full means that there is a person of great worth. I beg that this be handed over to the Bureau of Historiography'. All the Officials presented there congratulations and the Emperor ordered that it be sent to the Bureau of Historiography. During the 3rd month of the 1st year of the Chia-yu reign period the Director of the Astronomical Bureau said, 'The guest star has vanished, which is an omen of the departure of the guest'.

Earlier, during the 5th month in the 1st year of the Chih-ho reign period, the guest star appeared in the morning in the east guarding Tian-kuan. It was visible in the daytime, like Venus. It had pointed rays in the four directions and its colour was reddish-white. Altogether it was visible in daytime for 23 days."

Other accounts of the same event appear in the annals of the Liao Dynasty (a nomadic tribe of north China), and in Japanese chronicles.
Crab Supernova found Europe in the middle of the dark ages (500-1500AD)

First Universities will appear only after 34 years

- Bologna: 1088
- Paris: 1150
- Oxford: 1167
Crab Supernova was observed in the New World?

It was probably recorded by Anasazi Indian artists (in present-day Arizona and New Mexico), as findings in Navaho Canyon and White Mesa as well as in the Chaco Canyon National Park (NM) indicate.
- Crab Supernova: by April 17 1056 it was gone

- Crab Nebula was first observed in 1731 John Devis

- It was rediscovered in 1758 Charles Messier – comet like object

- Named as Crab Nebula only in 1840 William Parsons (Earl of Roses)

- In 20th Century comparing pictures from the different years it was observed that nebula is expanding

- Tracing the expansion back it was concluded that nebula must have become visible on Earth about 900 years ago

- Identified with the 1054 observations
Supernova

Tycho’s Nova 1572
Cassiopea, MW

Kepler’s Nova 1604
Ophiuchus MW

S Andromedae 1885

Hubble Telescope

Fritz Zwitsky named it Supernova
1926-1931

SN’s are explosions
Advent of Mechanics and Gravity

**Macroscopic Systems**

<table>
<thead>
<tr>
<th>Fast</th>
<th>Classical Mechanics</th>
<th>Galilean Relativity</th>
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<tbody>
<tr>
<td></td>
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<td>$t, \vec{r} \leftrightarrow t, \vec{r}'$</td>
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<thead>
<tr>
<th>Strong</th>
<th>Relativistic Mechanics</th>
<th>Special Theory of Relativity</th>
</tr>
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</tr>
</tbody>
</table>

**Newtonian Gravity**

\[
F = G \frac{m_1 m_2}{r^2}
\]

**General Theory of Gravitation**

\[
G^\mu_\nu = -8\pi G T_\mu_\nu
\]
Advent of the Nuclear and Particle Physics

Classical Mechanics

Relativistic Mechanics

Quantum Mechanics

Quantum Field Theory

Fast
Small

Microscopic

Atom - 1805

e - 1897

Atomic Nuclei - 1911

Model of Atom 1913

Proton 1919

Neutron 1932

Neutron Stars 1933!

Nuclear Forces 1934

With all reserve we advance the view that the supernovae represent the Transition from ordinary stars to neutron stars, which in their final stages consist of closely packet neutrons W.Baade and F. Zwicky, 1934 Phys. Rev. 45 (138)
<table>
<thead>
<tr>
<th>Small</th>
<th>Microscopic</th>
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</thead>
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<tr>
<td>Classical Physics</td>
<td>Quantum Physics</td>
</tr>
<tr>
<td>Classical Statistics</td>
<td>Quantum Statistics</td>
</tr>
</tbody>
</table>

**Advent of the Statistical Quantum Mechanics**

**Pauli Principle**

1925

**Stirling’s Approximation**

\[
\ln(n!) \approx n \cdot \ln(n) - n
\]

**Boltzmann Equation**

\[
S = k \log W
\]

**Fermi-Dirac Distributions**

\[
f(\epsilon) = \frac{1}{e^{\frac{(\epsilon - \mu)}{kT}}} + 1
\]

If \( T \to 0 \)

\[
f(\epsilon) = \begin{cases} 
1 & , \epsilon_k \leq \mu \equiv \epsilon_{Fermi} \\
0 & , \epsilon_k > \epsilon_{Fermi}
\end{cases}
\]
Stellar Physics = General Theory of Relativity + Quantum Statistical Mechanics

Oppenheimer, Volkoff and Tolman 1939

\[\frac{dp}{dt} = - \frac{\left[p(r) + \epsilon(r)\right] G \left[M(r) + 4\pi r^3 p(r)\right]}{r \left[r - 2GM(r)\right]}\]

**Equation of State**

\[M(r) = 4\pi \int_{0}^{r} \epsilon(r) r^2 dr\]

\[\epsilon(r) = \epsilon(p(r))\]

\[\epsilon(r) = \epsilon(\rho(r))\]

\[p(r) = p(\rho(r))\]

\[\epsilon(r) - \text{Total Energy Density}\]
Oppenheimer, Volkoff and Tolman 1939
Degenerate Fermi Gas Model

\[ f(\epsilon) = \begin{cases} 
1 & , \epsilon_k \leq \mu \equiv \epsilon_{\text{Fermi}} \\
0 & , \epsilon_k > \epsilon_{\text{Fermi}}
\end{cases} \]

\[ \epsilon = \frac{\gamma}{2\pi} \int_0^{k_{\text{Fermi}}} \sqrt{k^2 + m^2} \ k^2 \, dk \]

\[ p = \frac{1}{3} \frac{\gamma}{2\pi} \int_0^{k_{\text{Fermi}}} \frac{k^2}{\sqrt{k^2 + m^2}} \ k^2 \, dk \]

\[ \rho = \frac{\gamma}{2\pi} \int_0^{k_{\text{Fermi}}} k^2 \, dk \]

\[ \epsilon_{\text{Fermi}} \approx \frac{k_{\text{Fermi}}^2}{2m} \]

\[ M_{\text{max}} = 0.7M_\odot \]

\[ R \approx 10km \]

\[ \rho \approx 6 \times 10^9 \text{ton/cm}^3 \]
$10^8$ Gauss !?
Back to the Crab Nebula (the pulsar found in 1968)
Neutron Stars and Nuclear Physics

Limiting Conditions for Neutron Star
\[
\frac{MG}{R} < \frac{4}{9}
\]

Causal Limit
\[
M = 3.14 M_\odot \quad R = 13.4 \text{ km}
\]

Observations
\[
M \approx (1.3 - 1.5) M_\odot \quad R = 10 - 12 \text{ km}
\]

and not
\[
M_{max} = 0.7 M_\odot
\]

Neutron star is not a completely degenerate free Fermi Gas

Nuclear Interaction among neutrons should be taken into account
Nuclear Forces at Average Internucleon Distances

Starting with NN interaction

Any given nucleon feels the average nuclear field in which only total central and some LS part survived

And proton and neutron come almost identical in the nuclei
As a result average distribution of nucleons is not completely degenerate but close to it.

\[ M \approx 1.3 - 1.5 M_{\odot} \]
$M_{max} \approx 1.5 - 1.7 M_\odot$
The Largest neutron-star mass yet recorded has broad implication.

Physics Today Jan 2011

But now much of that speculation has Abruptly been laid to rest by a single astrophysical weighting.

- National Radio Astronomy in Green Bank
  Double Pulsar J1614-2230
Physics of Neutron Stars

Surface
- Hydrogen/Helium plasma
- Iron nuclei

Outer Crust
- Atomic nuclei
- Electron gas

Inner Crust
- Heavy atomic nuclei
- Relativistic electron gas
- Superfluid neutrons

Outer Core
- Neutrons, superconducting protons
- Electrons, muons

Inner Core
- Neutrons, protons, electrons, muons
- Hyperons ($\Sigma$, $\Lambda$, $\Xi$)
- Boson ($\pi$, $K$) condensates
- Deconfined (u,d,s) quarks / color-superconducting quark matter

Radius ~ 10 to 14 km, Mass ~ 1 to 2 M$_{\odot}$

F. Weber (SDSU, 2010)
Nuclear Forces at Short Distances: NN Interaction

- Cut-off
- Wood-Saxon type Parameterization
- Lattice
- Effective Range Interaction
- Meson Exchange Models: OBE
- Potential Models
- Effective Field Theories
- Perturbative QCD
- Higher order PDF's

Graph showing internucleon potential (MeV) vs. separation (fm). Key features include:
- Repulsive core
- Effective Range Interaction
- Meson Exchange Models: OBE
- Potential Models
- Effective Field Theories
- Perturbative QCD
- Higher order PDF's

Legend:
- $2\pi$
- $\rho, \omega, \sigma$
- $\pi$
Phenomenological NN Potentials

\[ H = - \sum_i \frac{\nabla_i^2}{2m} + \sum_{i<j} V_{i,j}^{2N} + \sum_{i<j<k} V_{i,j,k}^{3N} + \cdots \]

\[ H \Psi_A(r_1, \cdots, r_A) = E \Psi_A(r_1, \cdots, r_A) \]

\[ V^{2N} = V^{2N}_{EM} + V^{2N}_\pi + V^{2N}_R \]

\[ V^{2N}_R = V^c + V^{l2}L^2 + V^t S_{12} + V^{ls} L \cdot S + v^{ls2} (L \cdot S)^2 \]

\[ V^i = V_{int,R} + V_{core} \]

\[ V_{core} = \left[ 1 + e^{\frac{r-r_0}{a}} \right]^{-1} \]

60's
Nuclear Forces at Average Internucleon Distances

Starting with NN interaction

Any given nucleon feels the average nuclear field in which only total central and some LS part survived

And proton and neutron come almost identical in the nuclei
High Density Fluctuations/Short Range Nucleon Correlations in Nuclei
Probing Short Range Nucleon Correlations: Hard Processes

Two Nucleon Correlations

Three Nucleon Correlations
What we can learn about BB without detecting it?

- the Black Box has constituents
- the probe knocks-out one of such constituents without breaking it
- the remnant of the BB was a spectator to this action
\[ p_i = P_{BB} - P_R \]

\[ (q + p_i)^2 = m_c^2 \]

\[ -Q^2 + 2qp_i + m_i^2 = m_c^2 \]

\[ -Q^2 + q_- p_i^- + q_+ p_i^+ + m_i^2 = m_c^2 \]

\[ p_i^- = \frac{Q^2}{q_+} - \frac{q_-}{q_+} p_i^+ + \frac{m_c^2 - m_i^2}{q_+} \]

\[ p_i^- = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0} \]

\[ z \parallel q \]

\[ p_{i \pm} = E_i \pm p_{iz} \]

\[ q_{\pm} = q_0 \pm q \]

\[ Q^2 \quad \text{fixed} \]

\[ q_+ \rightarrow \infty \]

\[ q_+ \rightarrow 2q_0 \]

\[ \frac{q_-}{q_+} \quad \text{fixed} \]

\[ \frac{q_-}{q_+} \rightarrow 0 \]
\[ p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0} \]

\[ p_{i\pm} = E_i \pm p_{iz} \]

\[ p_{i-} = ? \quad \xrightarrow{\text{Invariant with respect to Lorentz transformation in } z} \quad \frac{p_{i-}}{P_{BB^+}} \]

\[ \frac{p_{i-}}{P_{BB^-}} \bigg|_{LAB} = \frac{Q^2}{2q_0 M_{BB}} \]

\[ \frac{p_{i-}}{P_{BB^-}} \bigg|_{IMF} = \left( \frac{E_i + p_{iz}}{E_{BB} + P_{BB}^z} \right)_{IMF} \approx \left( \frac{p_{iz}^z}{P_{BB}^z} \right)_{IMF} \]

\[ p_{i\perp} \ll p_{iz}^{IMF} \]
If \( BB = \text{nucleus} \) knocked out constituent is nucleon

**Correlation Parameter**

\[
\alpha = A \frac{p_{-}}{P_{BB}}
\]

**Momentum Fraction of Nucleus carried by the constituent nucleon**

\[\alpha > j - 1 \text{ at least } j\text{-nucleons involved in the scattering}\]

For sufficiently large \( Q^2 \)

\[
\frac{p_{i-}}{P_{BB}} \bigg|_{LAB} = \frac{Q^2}{2q_0 M_{BB}}
\]

\[
\alpha \approx x Bj = \frac{Q^2}{2m_N q_0}
\]
signatures for short range correlations

\[ x > 1 \quad \text{if only 2 nucleons then} \quad \frac{\sigma_A}{\sigma_D} \quad \text{scales} \]

\[ x > 2 \quad \text{if only 3 nucleons then} \quad \frac{\sigma_A}{\sigma_{A=3}} \quad \text{scales} \]

\[ x > j \quad \text{if only } j+1 \text{ nucleons then} \quad \frac{\sigma_A}{\sigma_{j+1}} \quad \text{scales} \]
\[ x_{Bj} > 1.5 \quad Q^2 \geq 1.4\text{GeV}^2 \]

\[ ^{12}\text{C}(e, e')X \]

\[ \frac{\sigma^{^{12}\text{C}}}{12} \]

\[ ^{3}\text{He}(e, e')X \]

\[ \frac{\sigma^{^{3}\text{He}}}{3} \]
signatures for short range correlations

\[ x > 1 \quad \text{at least 2 nucleons are needed} \]
\[ x > 2 \quad \text{at least 3 nucleons are needed} \]
\[ x > j \quad \text{at least } j+1 \text{ nucleons are needed} \]

**Prediction for Scaling**

\[ x > 1 \quad \text{if only 2 nucleons then} \quad \frac{\sigma_A}{\sigma_D} \quad \text{scales} \]
\[ x > 2 \quad \text{if only 3 nucleons then} \quad \frac{\sigma_A}{\sigma_{A=3}} \quad \text{scales} \]
\[ x > j \quad \text{if only } j+1 \text{ nucleons then} \quad \frac{\sigma_A}{\sigma_{j+1}} \quad \text{scales} \]
$x_{Bj} > 2$

$^{12}\text{C}(e, e')X$

$\frac{\sigma^{12}\text{C}}{12}$

$^{3}\text{He}(e, e')X$

$\frac{\sigma^{3}\text{He}}{3}$
Meaning of the scaling values

For $2 < x < 3$ \[ R \approx \frac{a_3(A_1)}{a_3(A_2)} \]

For $1 < x < 2$ \[ R \approx \frac{a_2(A_1)}{a_2(A_2)} \]

\[ R = \frac{A_2 \sigma[A_1(e,e')X]}{A_1 \sigma[A_2(e,e')X]} \]
What we Learned from $A(e,e')X$ Reactions

<table>
<thead>
<tr>
<th>nuclide</th>
<th>$a_{2N}(A)$</th>
<th>$a_{3N}(A)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}$</td>
<td>0.080±0.000±0.004</td>
<td>0.0018±0.0000±0.0006</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>0.154±0.002±0.033</td>
<td>0.0042±0.0002±0.0014</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>0.193±0.002±0.041</td>
<td>0.0055±0.0003±0.0017</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>0.227±0.002±0.047</td>
<td>0.0079±0.0003±0.0025</td>
</tr>
</tbody>
</table>

\[a_2(\text{^{12}C}) = 0.194\%\]
\[a_3(\text{^{12}C}) = 0.0055\%\]

\[a_2(\text{^{56}Fe}) = 0.227\%\]
\[a_3(\text{^{56}Fe}) = 0.0079\%\]
high energy inclusive probe at $x>1$ and large $Q^2$ can detect high density fluctuations

and measure their probabilities $a_2(A) \ a_3(A)$
Structure of these correlations/high density fluctuations
Carbon

\[ p + A \rightarrow pp (90^0 \text{ cm}) + n + X \text{ at BNL} \]
Brookhaven Experiment

A. Tang et al, PRL 2003

\[ F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)}, \]

\[ F = 0.43^{+0.11}_{-0.07} \quad \text{for } 275 \leq p_i, p_n \leq 550 \text{ MeV/c} \]

Theoretical Analysis

Piasecki, Sargsian, Frankfurt, Strikman, Watson, PRL 2007

\[ P_{pn/pX} = \frac{F}{T_n R} \]

relative probability of finding pn SRC in the “pX” configuration that contains a proton with \( p_i > k_F \).

\[ R \equiv \frac{\int_{\alpha_i^{\text{min}}}^{\alpha_i^{\text{max}}} \int_{p_{ti}^{\text{min}}}^{p_{ti}^{\text{max}}} \int_{\alpha_n^{\text{min}}}^{\alpha_n^{\text{max}}} \int_{p_{ln}^{\text{min}}}^{p_{ln}^{\text{max}}} D_{pn}(\alpha_i, p_{ti}, \alpha_n, p_{nt}, P_{R+}) \frac{d\alpha}{\alpha} d^2 p_t \frac{d\alpha_n}{\alpha_n} d^2 p_{ln} dP_{R+}}{\int_{\alpha_i^{\text{min}}}^{\alpha_i^{\text{max}}} \int_{p_{ti}^{\text{min}}}^{p_{ti}^{\text{max}}} \int_{\alpha_n^{\text{min}}}^{\alpha_n^{\text{max}}} \int_{p_{ln}^{\text{min}}}^{p_{ln}^{\text{max}}} S_{pn}(\alpha_i, p_{ti}, P_{R+}) \frac{d\alpha}{\alpha} d^2 p_t dP_{R+}}. \]
\[ P_{pn/pX} = 0.92^{+0.08}_{-0.18} \]

Expected: (Wigner counting)
\[ pn = \frac{2}{3}, \ pp = \frac{1}{3} \]

\[ \frac{P_{pp}}{P_{pn}} \leq \frac{1}{2} (1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04} \]

- 92% of the time two-nucleon correlations are proton and neutron
- at most 4% of the time proton-proton or neutron-neutron
neutron rate 92%

6p and 6n

Carbon

proton + A \rightarrow p + p + n + X

neutron rate 92%

calculated upper limit of proton rate 4%
e + A \rightarrow e' + p (> GeV) + n/p (300-600 MeV) + X

\[ P_{pn/pX} = 0.96 \pm 0.22 \]

\[ P_{pp/pn} = 0.056 \pm 0.018 \]
Counts

\[ \cos \gamma \]

Combined Analysis

Combined Analysis

92% of the time two-nucleon high density fluctuations are proton and neutron

at most 4% of the time proton-proton or neutron-neutron

\[
P_{pn/pX} = 0.92^{+0.08}_{-0.18}
\]

\[
\frac{P_{pp}}{P_{pX}} \leq \frac{1}{2} (1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}
\]

BNL data on \( A(p,2pn)X \)

Piasetzky, MS, Frankfurt, Strikman, Watson  PRL 2007

short range correlations in the range of 250-600 MeV/c are \( pn \) SRCs

\[
P_{pn/pX} = 0.96 \pm 0.22
\]

\[
P_{pp/pX} = 0.056 \pm 0.018
\]

JLAB data \( A(e,e'pn)X \)

R. Shneor et al. PRL 07
Press releases on SRC:
protonSRCfinal.pdf
EVA-SRC-discoverbnl.pdf
Protons Pair Up with Neutrons (from BNL News, pdf)
Science Magazine: Probing Cold Dense Nuclear Matter (pdf)
Nature Physics (Research Highlights: Unequal pairs (pdf))
Protons Pair Up With Neutrons, EurekAlert, May 29, 2008
Jefferson Lab in the News: Nuclear Pairs
Brookhaven National News: Protons Pair Up with Neutrons
Press release from Kent State University
ScienceDaily (Penn State University)
ScienceDaily (Penn State University)
ScientistLive (Penn State University)
On Target
Physics Today (July, 2008)
PHYSORG.com
NFC (in hebrew)
Tel Aviv University Press (in hebrew)
CERN Courier article: "Protons and neutrons certainly prefer each other's company"
(July, 2008)
R&D magazine
The A to Z of Nanotechnology
analitica-world
Matter News
Softpedia
News @ Old Dominion

from http://tauphy.tau.ac.il/eip
Some Conclusions

- We learned to how to probe directly the short range correlations in nuclei with relative momenta 250-600 MeV/c

- SRC’s are dynamically high-density fluctuations with strong angular correlations

- There is a strong suppression (factor of 20) of pp and nn SRCs as compared to pn SRCs

- this disparity is related to the dominance of the strong tensor force at intermediate to short distances
Explanation lies in the dominance of the **tensor** part in the NN interaction

\[ V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L} \vec{S} \]

\[ S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2 \]

\[ S_{12}|_{pp} = 0 \quad \text{Isospin 1 states} \]

\[ S_{12}|_{nn} = 0 \]

\[ S_{12}|_{pn} = 0 \]

\[ S_{12}|_{pn} \neq 0 \quad \text{Isospin 0 states} \]

M.S, Abrahanyan, Frankfurt, Strikman PRC, 2005
Explanation lies in the dominance of the tensor part in the NN interaction

\[
V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L} \vec{S}
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S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2
\]

Sciavilla, Wiringa, Pieper, Carlson  PRL, 2007

Isospin 1 states

\[
S_{12} |_{pp} = 0
\]

\[
S_{12} |_{nn} = 0
\]

\[
S_{12} |_{pn} = 0
\]

Isospin 0 states

\[
S_{12} |_{pn} \neq 0
\]
Nuclear momentum distribution at $k > k_F$ should reflect the dynamics of $V_{NN}$ rather than $V_{Nucl}$.

$$V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L} \vec{S}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2$$

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Isospin 1 states

$$S_{12}|_{pn} \neq 0$$

Isospin 0 states

Sciavilla, Wiringa, Pieper, Carlson  PRL,2007

- Nuclear momentum distribution at $k > k_F$ should reflect the dynamics of $V_{NN}$ rather than $V_{Nucl}$.
- Dominance of $pn$ short range correlations as compared to $pp$ and $nn$ SRCs

- Dominance of NN Tensor as compared to the NN Central Forces at $\leq 1\text{fm}$

- Two New Properties of High Momentum Component

- Energetic Protons in Neutron Rich Nuclei

- Implications

  *EMC-SRC - correlation*

  *Neutrino-Nuclei Interactions: NuTeV anomaly*

  *Protons in the Neutron Stars*
Dominance of NN Correlations

(Lippmann–Schwinger Equation)

\[
(E_B - \frac{k^2}{2m} - \sum_{i=2,\ldots,A} T_i)\psi_A = \sum_{i=2,\ldots,A} \int V(k - k'_{i})\psi_A(k, k'_{i}, \ldots k_j, \ldots k_A)\frac{d^3 k'}{(2\pi)^3} + \sum_{i=2,\ldots,A} \int V(k_i - k'_{i})\psi_A(k, k'_{i}, \ldots k_j, \ldots, k_A)\frac{d^3 k'}{(2\pi)^3},
\]

-if the potential decreases at large \(k\), like \(V(k) \sim \frac{1}{k^n}\) and \(n > 1\)

- then the \(k\) dependence of the wave function for \(k^2/2m_N \gg |E_B|\)

\[
\psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, \ldots k_A)
\]
- The same is true for relativistic equations as: Bethe-Salpeter or Weinberg Light Cone Equations

- From $\psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, \ldots k_A)$ follows at $p > k_F$

  $n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p)$

- Experimental observations

- Isospin composition?
From \[ \psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, \ldots, k_A) \] follows at \( p > k_F \)

\[ n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p) \] (1)

- Dominance of pn Correlations (neglecting pp and nn SRCs)

\[ n_{NN}(p) \approx n_{pn}(p) \approx n_{(d)}(p) \] (2)
- Define momentum distribution of proton & neutron

\[ n^A(p) = \frac{Z}{A} n_p^A(p) + \frac{A - Z}{A} n_n^A(p) \]

\[ \int n^A_{p/n}(p) d^3p = 1 \]  

- Now define

\[ I_p = \frac{Z}{A} \int_{k_F}^{600} n_p^A(p) d^3p \]

\[ I_n = \frac{A - Z}{A} \int_{k_F}^{600} n_n^A(p) d^3p \]

- and observe that in the limit of no pp and nn SRCs

\[ I_p = I_n \]

- Neglecting CM motion of SRCs

\[ \frac{Z}{A} n_p^A(p) \approx \frac{A - Z}{A} n_n^A(p) \]
First Property: Approximate Scaling Relation

- if contributions by pp and nn SRCs are neglected and the pn SRC is assumed at rest

- for $\sim k_F - 600 \text{ MeV/c}$ region:

$$x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p)$$

where $x_p = \frac{Z}{A}$ and $x_n = \frac{A-Z}{A}$. 
Realistic 3He Wave Function: Faddeev Equation

\[ x_n(p), \text{ GeV} \]

\[ x_n n_n \]

\[ x_p n_p \]

\[ 1/2 n_d \]

\[ \text{Ratio} \]

MS, arXiv:1210.3280
Realistic $^3$He Wave Function: Correlated Gaussian Basis
T. Neff & W. Horiuchi

April 2013
Be9 Variational Monte Carlo Calculation:

Robert Wiringa  

http://www.phy.anl.gov/theory/research/momenta/
Be10 Variational Monte Carlo Calculation:

Robert Wiringa
Second Property:

Using Definition: \[ n^A(p) = \frac{Z}{A} n^A_p(p) + \frac{A-Z}{A} n^A_n(p) \]

Approximations:
\[ n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p) \]
\[ n_{NN}(p) \approx n_{pn}(p) \approx n_{(d)}(p) \]

One Obtains
\[ x_p \cdot n^A_p(p) \approx x_n \cdot n^A_n(p) \approx \frac{1}{2} a_{NN}(A, y)n_d(p) \]

where \( y = |1-2x_p| = |x_n - x_p| \)

- \( a_{NN}(A, 0) \) corresponds to the probability of \( pn \) SRC in symmetric nuclei
- \( a_{NN}(A, 1) = 0 \) according to our approximation of neglecting \( pp/nn \) SRCs
Second Property: Fractional Dependence of High Momentum Component

\[ a_{NN}(A, y) \approx a_{NN}(A, 0) \cdot f(y) \quad \text{with} \quad f(0) = 1 \quad \text{and} \quad f(1) = 0 \]

\[ f(|x_p - x_n|) = 1 - \sum_{j=1}^{n} b_i |x_p - x_x|^i \quad \text{with} \quad \sum_{j=1}^{n} b_i = 0 \]

In the limit \( \sum_{j=1}^{n} b_i |x_p - x_x|^i \ll 1 \) \quad Momentum distributions of p & n are inverse proportional to their fractions

\[ n_{p/n}^{A} (p) \approx \frac{1}{2x_{p/n}} a_2(A, y) \cdot n_d(p) \]
Observations: High Momentum Fractions

\[ n_{p/n}^A(p) \approx \frac{1}{2x_{p/n}} a_2(A, y) \cdot n_d(p) \]

\[ P_{p/n}(A, y) = \frac{1}{2x_{p/n}} a_2(A, y) \int_{k_F}^{\infty} n_d(p) d^3p \]

<table>
<thead>
<tr>
<th>A</th>
<th>Pp(%)</th>
<th>Pn(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>27</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>56</td>
<td>27</td>
<td>23</td>
</tr>
<tr>
<td>197</td>
<td>31</td>
<td>20</td>
</tr>
</tbody>
</table>

M.S. 2012, Nucl-Th
Observations: High Momentum Fractions

\[ P_{p/n}(A, y) = \frac{1}{2x_{p/n}} a_2(A, y) \int_{k_F}^{\infty} n_d(p) d^3p \]

Checking for He3

Energetic Neutron

\[ E_{pkin}^p = 14 \text{ MeV} \ (p = 157 \text{ MeV/c}) \]
\[ E_{nkin}^n = 19 \text{ MeV} \ (p = 182 \text{ MeV/c}) \]

Energetic Neutron
(Neff & Horiuchi)

\[ E_{pkin}^p = 13.97 \text{ MeV} \]
\[ E_{nkin}^n = 18.74 \text{ MeV} \]
Table 1: Kinetic energies (in MeV) of proton and neutron

<table>
<thead>
<tr>
<th>A</th>
<th>y</th>
<th>$E_{kin}^p$</th>
<th>$E_{kin}^n$</th>
<th>$E_{kin}^p - E_{kin}^n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8$He</td>
<td>0.50</td>
<td>30.13</td>
<td>18.60</td>
<td>11.53</td>
</tr>
<tr>
<td>$^6$He</td>
<td>0.33</td>
<td>27.66</td>
<td>19.06</td>
<td>8.60</td>
</tr>
<tr>
<td>$^9$Li</td>
<td>0.33</td>
<td>31.39</td>
<td>24.91</td>
<td>6.48</td>
</tr>
<tr>
<td>$^3$He</td>
<td>0.33</td>
<td>14.71</td>
<td>19.35</td>
<td>-4.64</td>
</tr>
<tr>
<td>$^3$H</td>
<td>0.33</td>
<td>19.61</td>
<td>14.96</td>
<td>4.65</td>
</tr>
<tr>
<td>$^8$Li</td>
<td>0.25</td>
<td>28.95</td>
<td>23.98</td>
<td>4.97</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>0.2</td>
<td>30.20</td>
<td>25.95</td>
<td>4.25</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>0.14</td>
<td>26.88</td>
<td>24.54</td>
<td>2.34</td>
</tr>
<tr>
<td>$^9$Be</td>
<td>0.11</td>
<td>29.82</td>
<td>27.09</td>
<td>2.73</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>0.09</td>
<td>33.40</td>
<td>31.75</td>
<td>1.65</td>
</tr>
</tbody>
</table>
Implications: Protons are more energetic in neutron reach Nuclei

- Can be checked in A(e,e′p) Reaction

(Or Hen & Eli Piasezky)

\[ R_A = \frac{\int_{k_F}^{\infty} \sigma_A(p_{in}) \, d^3 p_{in}}{\int_0^{k_F} \sigma_A(p_{in}) \, d^3 p_{in}} \]

\[ R = \frac{R_A}{R_{C12}} \]
Implications: Energetic Protons in neutron rich Nuclei

Implications: Protons are more modified in neutron rich nuclei

- Flavor Dependence of EMC effect
- Different explanation of NuTev Anomaly
- Can be checked in neutrino-nuclei or in pvDIS processes
What these studies can tell us about structure of Neutron Stars?

Number of nucleons beyond the Fermi Energy

\[ P_{p/n}(A, y) = \frac{1}{2x_{p/n}} a_2(A, y) \int_{k_F}^{\infty} n_d(p) d^3p \]

\[ a_2(A, y) = a_2(\rho, y) \]

\[ a_2(\rho, y) \big|_{\rho \to \infty} = ? \]
Implications: For Nuclear Matter

\[ P_{p/n}(A, y) = \frac{1}{2x_{p/n}} a_2(A, y) \int_{k_F}^{\infty} n_d(p) d^3p \]

Table 1: The results for \( a_2(A, y) \)

<table>
<thead>
<tr>
<th>A</th>
<th>y</th>
<th>This Work</th>
<th>Frankfurt et al</th>
<th>Egiyan et al</th>
<th>Famin et al</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^3)He</td>
<td>0.33</td>
<td>2.07±0.08</td>
<td>1.7±0.3</td>
<td></td>
<td>2.13±0.04</td>
</tr>
<tr>
<td>(^4)He</td>
<td>0</td>
<td>3.51±0.03</td>
<td>3.3±0.5</td>
<td>3.38±0.2</td>
<td>3.60±0.10</td>
</tr>
<tr>
<td>(^9)Be</td>
<td>0.11</td>
<td>3.92±0.03</td>
<td></td>
<td></td>
<td>3.91±0.12</td>
</tr>
<tr>
<td>(^{12})C</td>
<td>0</td>
<td>4.19±0.02</td>
<td>5.0±0.5</td>
<td>4.32±0.4</td>
<td>4.75±0.16</td>
</tr>
<tr>
<td>(^{27})Al</td>
<td>0.037</td>
<td>4.50±0.12</td>
<td>5.3±0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{56})Fe</td>
<td>0.071</td>
<td>4.95±0.07</td>
<td>5.6±0.9</td>
<td></td>
<td>4.99±0.5</td>
</tr>
<tr>
<td>(^{64})Cu</td>
<td>0.094</td>
<td>5.02±0.04</td>
<td></td>
<td></td>
<td>5.21±0.20</td>
</tr>
<tr>
<td>(^{197})Au</td>
<td>0.198</td>
<td>4.56±0.03</td>
<td>4.8±0.7</td>
<td></td>
<td>5.16±0.22</td>
</tr>
</tbody>
</table>
\[ a_2(A, y) \equiv a_2(\rho, y), \quad y = |1 - 2x_p|, \quad x_p \equiv \frac{Z}{A} \]

(1) \[ a_2(A, y) = a_2^{\text{sym}}(A) \cdot f(y) \]

(2) For \( a_2^{\text{sym}}(A) \), we analyze data for symmetric nuclei and for other A's use the relation where

\[ a_2^{\text{sym}}(A) = C \cdot \langle \rho_A^{2, \text{sym}} \rangle \]

\[ \langle \rho_A^{2, \text{sym}} \rangle = \frac{1}{A} \int \rho_{A, \text{sym}}(r)^2 d^3r \]

(3) Neglecting contributions due to pp and nn SRCs one obtains boundary conditions

\[ f(0) = 1 \quad \text{and} \quad f(1) = 0 \]
Implications: For Nuclear Matter

\[ a_2(A, y) = a_2(A, 0) f(y) \]

\[ a_2(A, 0) = C \int \rho_A^2(r) d^3r \]

\[ C = 49.1 \pm 2.6 \]
Implications: For Nuclear Matter

\[ a_2(A, y) = a_2(A, 0) f(y) \]

Fitting \( f(y) \)

- 6 data points
- 2 boundary conditions due to the neglection of pp/nn SRCs
  \( f(0) = 1 \) and \( f(1) = 0 \)
- 2 more boundary conditions due to
  \( y \to 1 \) and \( y \to 0 \)
  corresponds to \( A \to \infty \)
  \( f'(0) = f'(1) = 0 \)
- 1 more positiveness of \( f(y) \)

\[ f(y) \approx (1 + (b - 3)y^2 + 2(1 - b)y^3 + by^4) \]

\( b \approx 3 \)
Extrapolation to infinite and superdense nuclear matter

\[ a_2(A, y) = a_2^{\text{sym}}(A) \cdot f(y) \quad \text{with} \quad a_2^{\text{sym}}(A) = C \cdot \langle \rho_{A, \text{sym}}^2 \rangle \]

For the symmetric nuclear matter at saturation densities \( \rho_0 \) using: \( R = r_0 \cdot A^{\frac{1}{3}} \) we obtain:

\[ \langle \rho^2 \rangle_{\text{sym}}^{\text{INM}} = \frac{1}{A} \int \rho_{A, \text{sym}}^2(r) d^3r = \frac{4\pi}{3} \rho_0^2 r_0^3 \approx 0.143 \text{ fm}^{-3} \]

\[ a_2(\rho_0, 0) \approx 7.03 \pm 0.41 \]

compare

\[ a_2(\rho_0, 0) \approx 8 \pm 1.24 \]

C.Ciofi degli Atti, E. Pace, G.Salme, PRC 1991
Consider $\beta$ equilibrium $e - p - n$ superdense asymmetric nuclear matter at the threshold of URCA processes $x_p = \frac{1}{9} (y = \frac{7}{9})$.

At $x_p < \frac{1}{9}$ the URCA processes

$$n \rightarrow p + e^- + \bar{\nu}_e, \quad p + e^- \rightarrow n + \nu_e$$

will stop in the standard model of superdense nuclear matter consisting of degenerate protons and neutrons.
Implications: For Nuclear Matter

\[ P_{p/n}(A, y) = \frac{1}{2x_{p/n}} a_2(A, y) \int_{k_F}^{\infty} n_d(p) d^3p \]

For \( x_p = \frac{1}{9} \) and \( y = \frac{7}{9} \)

and using \( k_{F,N} = (3\pi^2 x_N \rho)^{\frac{1}{3}} \)
For \( x_p = \frac{1}{9} \) and \( y = \frac{7}{9} \) and using \( k_{F,N} = (3\pi^2 x_N \rho)^{\frac{1}{3}} \):

\[
P_{p/n}(\rho,y) = \frac{a_2(\rho,y)}{2x_{p/n}} \int_{k_F} n_d(k) d^3k
\]
Some Possible Implication of our Results

Cooling of Neutron Star:

Large concentration of the protons above the Fermi momentum will allow the condition for Direct URCA processes $p_p + p_e > p_n$ to be satisfied even if $x_p < \frac{1}{9}$. This will allow a situation in which intensive cooling of the neutron stars will be continued well beyond the critical point $x_p = \frac{1}{9}$.

Superfluidity of Protons in the Neutron Stars:

Transition of protons to the high momentum spectrum will smear out the energy gap which will remove the superfluidity condition for the protons. This will also result in significant changes in the mechanism of generation of neutron star magnetic fields.
Protons in the Neutron Star Cores:

The concentration of protons in the high momentum tail will result in proton densities \( \rho_p \sim p_p^3 \gg k_{F,p}^3 \). This will result in an equilibrium condition with "neutron skin" effect in which large concentration of protons will populate the core rather than the crust of the neutron star. This situation may provide very different dynamical conditions for generation of magnetic fields of the stars.

Isospin Locking and Large Masses of Neutron Stars

With an increase of the densities more and more protons move to the high momentum tail where they are in short range tensor correlations with neutrons. In this case on will expect that high density nuclear matter will be dominated by configurations with quantum numbers of tensor correlations \( S = 1 \) and \( I = 0 \). In such scenario protons and neutrons at large densities will be locked in the NN isosinglet state. Such situation will double the threshold of inelastic excitation from \( NN \rightarrow N\Delta \) to \( NN \rightarrow \Delta\Delta(NN^*) \) transition thereby stiffening the equation of the state. This situation my explain the observed neutron star masses in Ref.[?] which are in agreement with the calculation of equation state that include only nucleonic degrees of freedom.
Limitation of the Model

- \( pp/nn \) Correlations are neglected
- \( pn \) SRC is at Rest
- 3N SRCS
- non-nucleonic component of SRCS

Identical Effects on proton and neutron distributions?

\[
x_p^\gamma \cdot n_p^A(p) \approx x_n^\gamma \cdot n_n^A(p)
\]

\[
n_{p/n}^A(p) \approx \frac{1}{2x_{p/n}^\gamma} a_2(A, y) \cdot n_d(p)
\]

\( \gamma < 1 \)
CD-Bonn

$\rho = 0.16 \text{ fm}^{-3}$

$T = 5 \text{ MeV}$

Av18

N3LO

A.Rios, A. Polls and W. H. Dickhoff,
Private Communication
Is the Observed Effects Universal for Two Component Asymmetric Fermi Systems?

- Start with Two Component Asymmetric Degenerate Fermi Gas
- Asymmetric: \( \rho_1 \ll \rho_2 \)
- Switch on the short-range interaction between two-component
- While interaction between each components is weak
- Spectrum of the small component gas will strongly deform

Cold Atoms
Is the Observed Effect Universal to Two Component Asymmetric Fermi Systems?

![Graph showing density of n and p particles as a function of momentum (k, GeV/c).]
Conclusions and Outlook

- We observe two new properties of high momentum distribution of proton and neutron in nuclei
- Predicting more energetic/virtual protons in neutron reach matter
- Explains the form of the EMC-SRC correlation (preliminary)
- Explains NuTeV anomaly (preliminary)
- May have strong implication for protons in neutron stars Cooling & Magnetic Fields
Some Outlook

- More Symmetric Nuclei
- Measurements of $pp/nn$
- $3N$ SRCS
- Nuclei with large asymmetry parameters
- Break-down of nucleon framework