Proton-neutron pairing and alpha-like correlations in nuclei
Trento, September 19 - 23, 2016

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Many Thanks to Stefan Frauendorf, Nicu Sandulescu, Michelangelo Sambataro, and Marlene Assie

ECT*
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IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
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Outline

Introduction

Observables and review of the experimental status:

- Binding energy differences
- Low-lying states in odd-odd self conjugate nuclei
- Coriolis effects
- Pairing vibrations
- $\beta$ – decay

Direct Reactions

Quartet correlations

Summary
Atomic nuclei constitute unique many body systems of strongly interacting fermions. Their properties and structure, are of paramount importance to many aspects of physics.

Many of the phenomena encountered in nuclei share common basic physics ingredients with other mesoscopic systems, thus making nuclear structure research relevant to other areas of contemporary research, for example in condensed matter and atomic physics.

These are exciting times in the field of physics of nuclei:

Existing and planned rare isotope beam facilities worldwide and advanced detector systems with increased sensitivity and resolving power not only will allow us to answer some important questions we have today, but most likely will open up a window to new and unexpected phenomena.

New developments in theory and computer power are shaping a path to a predictive theory of nuclei and reactions.
The Physics of Nuclei: Science Drivers

<table>
<thead>
<tr>
<th>Nuclear Structure</th>
<th>Nuclear Astrophysics</th>
<th>Tests of Fundamental Symmetries</th>
<th>Applications of Isotopes</th>
</tr>
</thead>
</table>

Overarching questions from NSAC Long Range Plan 2015

<table>
<thead>
<tr>
<th>How are nuclei made and organized?</th>
<th>Where do nuclei and elements come from?</th>
<th>Are neutrinos their own antiparticles?</th>
<th>What are practical and scientific uses of nuclei?</th>
</tr>
</thead>
<tbody>
<tr>
<td>How are nuclei made and organized?</td>
<td>Where do nuclei and elements come from?</td>
<td>Are neutrinos their own antiparticles?</td>
<td>What are practical and scientific uses of nuclei?</td>
</tr>
<tr>
<td>What is the nature of dense nuclear matter?</td>
<td>What combinations of neutrons and protons can form a bound atomic nucleus?</td>
<td>Why is there more matter than antimatter in the present universe?</td>
<td>What are practical and scientific uses of nuclei?</td>
</tr>
<tr>
<td>How do neutrinos affect element synthesis?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Overarching questions are answered by rare isotope research

Rare Isotope Beams

*State of the art* instrumentation

Theory
Theory is when you know everything but nothing works.

Practice is when everything works but no one knows why.

In this lab, theory and practice are combined: nothing works and no one knows why.
The Nuclear Landscape

**Proton drip-line**
- Mirror symmetry
- $p$ and $2p$ tunneling
- Spin triplet superconductivity
- (T=0 pairing)
- rp-process
- Novae, X-ray bursts

**Neutron drip-line**
- Halos, Skins
- Pairing at low density
- New shell structure
- New collective modes
- r-process
- Stars, Supernovae

**Heavy Elements**
- Shell stability
- Island of SHE
Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State

A. Bohr, B. R. Mottelson, and D. Pines

Dept. of Theoretical Physics, University of Copenhagen, Copenhagen, Denmark, and Nordisk Institut for Teoretisk Atomfysik, Copenhagen, Denmark

(Received January 7, 1958)

The evidence for an energy gap in the intrinsic excitation spectrum of nuclei is reviewed. A possible analogy between this effect and the energy gap observed in the electronic excitation of a superconducting metal is suggested.
Many properties are influenced by pairing correlations:

- Gap in the excitation spectra of even-A nuclei
- Odd-even mass differences
- Rotational moments of inertia and particle alignments

It is, of course, a subject of relevance to other finite Fermion systems such as $^3$He clusters, Fermi-gas condensates, quantum dots, metal clusters, ....
The Nuclear Landscape

N=Z - line
Mirror symmetry
p and 2p tunneling
**Spin triplet superconductivity**
(T=0 pairing)
rp-process
Novae, X-ray bursts
Review

Overview of neutron–proton pairing

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N=Z nuclei, unique systems to study \( np \) correlations

As you move out of N=Z, \( T=1 \) \( nn \) and \( pp \) pairs will start to dominate. \( T=0 \) excited states.

Role of isoscalar (\( T=0 \)) and isovector (\( T=1 \)) pairing

- Large spatial overlap of \( n \) and \( p \)
- Pairing vibrations (normal system)
- Pairing rotations (superfluid system)

Does isoscalar pairing give rise to collective modes?

Possible signals

- Binding energy differences
- Low-lying states of odd-odd self-conjugate nuclei
- Rotational properties: moments of inertia, alignments
- Beta decay
- Direct reactions
Single-/shell model


\[ H = -G_0 \sum_\mu S_\mu^+ S_\mu - G_1 \sum_m P_\mu^+ P_m \]

T=0, S=1 pairs

T=1, S=0 pairs
\[ x = \frac{G_1}{G} \]
Binding Energy Differences
Single-/shell model

**Graph Description**

- **Axes:**
  - Y-axis: $E - E_{\infty}$
  - X-axis: $X$, representing isoscalar and isovector variables.

- **Curves:**
  - Three curves are plotted for different values of $N$ and $S$.
    - $N=4$: Green line
    - $N=6$, $T=1$, $S=0$: Red line
    - $N=6$, $T=0$, $S=1$: Black line
    - $N=8$: Black dashed line

- **SU(4)**: The curves are labeled with the SU(4) symmetry.
Single-$j$ shell model

$L=0$ matrix elements

$V_{ls} \rightarrow 0 \quad l$-shell

$V_{ls} \rightarrow \infty \quad j$-shell

$v = x V_{T=1,J=0} + (1-x) V_{T=0,J=1}$

\[ E \sim -G(N - \nu/2)\Omega = -(2\Delta)(N - \nu/2) \]
Must compare states with the same isospin:

**T = 0 states**: Use the even-even N=Z neighbors as a reference

**T = 1 states**: Use the even-even isobaric analogs as a reference

T=0 states give a pair gap

\[ \Delta \approx 2 \Delta \]

T=1 states give no pair gap

\[ 2\Delta \sim 2 \times 12 \text{ MeV} \div A^{1/2} \]
### Two ingredients

<table>
<thead>
<tr>
<th></th>
<th>Even-even</th>
<th>T=0</th>
<th>E₀</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Odd-odd</td>
<td>T=0</td>
<td>E₀</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T=1</td>
<td>E₀ + 2Δₜ=1 + Eₛ(0)</td>
</tr>
<tr>
<td></td>
<td>Even-even</td>
<td>T=1</td>
<td>E₀ + 2Δₜ=1 + Eₛ(1)</td>
</tr>
<tr>
<td></td>
<td>Odd-even</td>
<td>T=1/2</td>
<td>E₀ + Δₜ=1 + Eₛ(1/2)</td>
</tr>
</tbody>
</table>
\[ \Delta \sim 12 \text{MeV}/A^{1/2} \]

\[ \text{Sym} \sim 75 \text{MeV}/A \times T(T+1) \]

\[ 2\Delta \sim 2 \times 12 \text{MeV}/A^{1/2} \]

\[ \text{Odd} \quad N=Z+1 ; T=1/2 \]

\[ \Delta + \text{Sym} \]
Ground state of odd-odd self conjugate nuclei
\[ \Delta T = 1 \]

\[ E_{S}(T) \]

\[ 2\Delta_{T=1} \]
Low-lying States in odd-odd N=Z Nuclei
Quasideuteron configurations in odd-odd $N=Z$ nuclei

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<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Expt.</th>
<th>Eq. (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$B₅</td>
<td>7.5(32)</td>
<td>5.32</td>
</tr>
<tr>
<td>$^{14}$N₇</td>
<td>0.05(2)</td>
<td>0.75</td>
</tr>
<tr>
<td>$^{18}$F₉</td>
<td>20(4)</td>
<td>14.65</td>
</tr>
<tr>
<td>$^{22}$Na₁₁</td>
<td>5.0(3)</td>
<td>3.70</td>
</tr>
<tr>
<td>$^{26}$Al₁₃</td>
<td>8(2)</td>
<td>6.78</td>
</tr>
<tr>
<td>$^{30}$P₁₅</td>
<td>1.3(1)</td>
<td>2.33</td>
</tr>
<tr>
<td>$^{34}$Cl₁₇</td>
<td>0.23(2)</td>
<td>0.005</td>
</tr>
<tr>
<td>$^{38}$K₁₉</td>
<td>0.47(4)</td>
<td>0.35</td>
</tr>
<tr>
<td>$^{42}$Sc₂₁</td>
<td>11(4)</td>
<td>15.62</td>
</tr>
<tr>
<td>$^{46}$V₂₃</td>
<td>6.40</td>
<td></td>
</tr>
<tr>
<td>$^{50}$Mn₂₅</td>
<td>6.34</td>
<td></td>
</tr>
<tr>
<td>$^{54}$Co₂₇</td>
<td>11.82</td>
<td></td>
</tr>
<tr>
<td>$^{58}$Cu₂₉</td>
<td>3.44</td>
<td></td>
</tr>
<tr>
<td>$^{62}$Ni₄₁</td>
<td>15.52</td>
<td></td>
</tr>
</tbody>
</table>
Low level density near the ground state
Gap like in even-even nuclei
Coriolis Effects
Coriolis effects

\[ j \omega \sim 2\Delta \]

Is there any difference in their response to rotational motion?

Goodman, Sheik, Rowley, Frauendorf, Satula, Wyss
Delayed $g_{9/2}^2$ alignment in the N = Z nucleus $^{72}$Kr

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PHYSICAL REVIEW C, VOLUME 65, 051303(R)

Delayed alignments in the N = Z nuclei $^{84}$Mo and $^{88}$Ru

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Unravelling the band crossings in $^{68}$Se and $^{72}$Kr: The quest for $T=0$ pairing

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Detailed spectroscopy from GAMMASPHERE + Microball + Neutron Array + FMA data

Resolve discrepancies in yrast and near yrast bands

Differential Doppler shift measurements indicate different shapes for the bands in $^{72}$Kr
No clear cut evidence for delayed alignments
Difficult issue, shape degrees of freedom need to be understood
Description of rotating $N = Z$ nuclei in terms of isovector pairing

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(Received 17 May 2004; revised manuscript received 15 March 2005; published 27 June 2005)

A systematic investigation of the rotating $N = Z$ even-even nuclei in the mass $A = 58 - 80$ region has been performed within the frameworks of the Cranked Relativistic Mean field, Cranked Relativistic Hartree Bogoliubov theories and cranked Nilsson-Strutinsky approach. Most of the experimental data is well accounted for in the calculations. The present study suggests that there is strong isovector $np$-pair field at low spin, the strength of which is defined by the isospin symmetry. At high spin, the isovector pair field is destroyed and the data are well described by the calculations assuming zero pairing. No clear evidence for the existence of the isoscalar $t = 0$ $np$-pairing has been obtained in the present investigation.
Recent work by Ramon Wyss et al. Phys. Rev C76 011301 (2007) on decay properties of rotational bands in $^{73}$Kr and $^{75}$Rb may suggest the development of dynamical $T=0$ pairing collectivity at high spins.
Quasideuteron alignment
Pairing Vibrations
PAIR CORRELATIONS AND
DOUBLE TRANSFER REACTIONS

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UNIVERSITY OF COPENHAGEN,
COPENHAGEN, DENMARK

ISOVECTOR PAIRING VIBRATIONS

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and

Ole HANSEN and O. NATHAN
The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark.
Collective pairing vibrations near closed shells


\[ H = \frac{1}{2} D (N_2 - N_1) - G_0 \sum_\mu S_\mu^+ S_\mu - G_1 \sum_m P_m^+ P_m \]

\[ 2 \Omega G_j / D < 1 \]

\[ \chi_j = G_j / G_{\text{crit}} \]
\[ \frac{G_1}{G_{\text{crit}}} \]

\[ \frac{1}{1} \]

\[ \frac{1}{1} \]

\[ \frac{G_0}{G_{\text{crit}}} \]

\[ \hbar \omega \sim D \left(1 - x \right)^{1/2} \]
N=Z nuclei
Collective $T=0$ pairing in $N=Z$ nuclei?  
Pairing vibrations around $^{56}$Ni revisited

A.O. Macchiavelli, P. Fallon, R.M. Clark, M. Cromaz, M.A. Deleplaque,  
D. Ward

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Table 1  
Properties of pairing vibrational phonons

<table>
<thead>
<tr>
<th>Closed shells</th>
<th>Phonon energy (MeV)</th>
<th>Single-particle level spacing (MeV) b)</th>
<th>$G/G_{crit}$</th>
<th>$1/A^{1/3}$ a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$Ca</td>
<td>$0.8 \ (T=1)$</td>
<td>5–6</td>
<td>$\sim 1$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$4.9 \ (T=0)$</td>
<td></td>
<td>$\sim 0.2$</td>
<td></td>
</tr>
<tr>
<td>$^{56}$Ni</td>
<td>$1.5 \ (T=1)$</td>
<td>4–5</td>
<td>$\sim 0.9$</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>$4.0 \ (T=0)$</td>
<td></td>
<td>$\sim 0.2$</td>
<td></td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>2.3 (neutrons)</td>
<td>3–4</td>
<td>$\sim 0.55$</td>
<td>0.58</td>
</tr>
</tbody>
</table>

a) Normalized to 1 for $^{40}$Ca; b) From Ref. [16].

Study binding energies around closed shells ($^{40}$Ca and $^{56}$Ni)  
$T=0$ Energy comparable with single particle separation - low collectivity.  
$T=1$ Energy consistent with collective excitations.
Isomeric-decay spectroscopy following projectile fragmentation of a $^{107}$Ag beam at GSI. RISING,

Low-lying structure supports a preference for $T = 1$ states in $T_z = 0$ odd–odd nuclei at low excitation energies associated with a $T = 1$ neutron–proton pairing gap.

Comparison with Projected Shell Model calculations.
β– Decay
Gamow-Teller $\beta$ Decay

(N-1,Z+1) \hspace{1cm} N=Z \hspace{1cm} (N+1,Z-1)

even-even \hspace{1cm} odd-odd \hspace{1cm} even-even

$0^+ \hspace{1cm} T=1$

log $t \leq 4 \hspace{1cm} 1^+ \hspace{1cm} T=0$

log $t \leq 4 \hspace{1cm} 0^+ \hspace{1cm} T=1$

log $t \leq 4 \hspace{1cm} 0^+ \hspace{1cm} T=1$

Hindered Gamow-Teller Decay to the Odd-Odd $N = Z$ $^{62}$Ga: Absence of Proton-Neutron $T = 0$ Condensate in $A = 62$

Other signatures
E2\(^+\), B(E2) ratios in Te and Xe isotopes close to \(^{100}\)Sn.

Super-allowed alpha decay
“Tour de Force” EXOGAM Experiment at GANIL

<table>
<thead>
<tr>
<th>State</th>
<th>E (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td>0</td>
</tr>
<tr>
<td>$0^+$</td>
<td>0</td>
</tr>
<tr>
<td>$0^+$</td>
<td>0</td>
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<td>$0^+$</td>
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</tr>
<tr>
<td>$0^+$</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$^{92}$Pd Exp.</th>
<th>$^{92}$Pd SM</th>
<th>$^{92}$Pd $T = 0$</th>
<th>$^{92}$Pd $T = 1$</th>
<th>No np</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,536</td>
<td>2,466</td>
<td>2,600</td>
<td>2,749</td>
<td>2,633</td>
</tr>
<tr>
<td>1,786</td>
<td>1,708</td>
<td>1,518</td>
<td></td>
<td>1,417</td>
</tr>
<tr>
<td>874</td>
<td>878</td>
<td>797</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diagram showing levels and transitions for $J = 9$.
Transfer Reactions
NOTE ON THE TWO-NUCLEON STRIPPING REACTION

SHIRO YOSHIDA
Radiation Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania

Received 9 February 1962

Abstract: The magnitude of the two-nucleon stripping reactions is calculated using the pair interaction model. The calculation also is applied to final states of collective type. For some types of reaction a collective enhancement of the reaction cross section is predicted.

ISOVECTOR PAIRING VIBRATIONS

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Chapter 3

TWO-NEUTRON TRANSFER REACTIONS

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Two particle transfer reactions like (t,p) or (p,t), where 2 nucleons are deposited or picked up at the same point in space provide a specific tool to probe the amplitude of this collective motion.

The transition operators $< f | a^+ a^+ | i >$, $< f | a a | i >$ are analogous to the transition probabilities $BE2$’s on the quadrupole case.
A\[s \rightarrow A+2\[turns\]

\[\Sigma (A_{gs} \rightarrow A+2_{gs})\]

\[\sim \Omega^2\]

Superfluids

\[\sim (\Delta/G)^2\]

Vibrations

\[\sim (n+1)\]

Closed shell

Single Particle

Systematic relative measurements and within a given nucleus.
Pair-transfer probability in open- and closed-shell Sn isotopes

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Surface interaction

![Graph showing surface interaction with A on the x-axis and Strength on the y-axis.]
The results from the Two j-shells model
\[ \frac{d\sigma}{d\Omega} \approx 2.5\frac{d\sigma}{d\Omega_{sp}} \]
(\(^3\text{He},p\)) Transfer Reactions

\[ \sigma \quad ? \]

T=0 J=0  \quad T=0 J=1  

np  

T=1 J=0  

Even-even  \quad Odd-odd

\((\(^3\text{He},p\)) - \quad L=0\) transfer

Measure the \(np\) transfer cross section to T=1 and T=0 states

Both absolute \(\sigma(T=0)\) and \(\sigma(T=1)\) and relative \(\sigma(T=0) / \sigma(T=1)\) tell us about the character and strength of the correlations
Deuteron Transfer in $N = Z$ Nuclei

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<table>
<thead>
<tr>
<th>Limit</th>
<th>Reaction</th>
<th>$C_T^2 = 0$</th>
<th>$C_T^2 = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b/a = 0$</td>
<td>EE $\rightarrow$ OO$_{T=0}$</td>
<td>$\frac{1}{2} (N_b + 6)$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>EE $\rightarrow$ OO$_{T=1}$</td>
<td>0</td>
<td>$\frac{1}{2} (N_b + 6)$</td>
</tr>
<tr>
<td>$b/a \ll -1$</td>
<td>EE $\rightarrow$ OO$_{T=0}$</td>
<td>$N_b + 3$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>EE $\rightarrow$ OO$_{T=1}$</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>$b/a \gg +1$</td>
<td>EE $\rightarrow$ OO$_{T=0}$</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>EE $\rightarrow$ OO$_{T=1}$</td>
<td>0</td>
<td>$N_b + 3$</td>
</tr>
</tbody>
</table>

SU(4)

Isoscalar

Isovector
Collective pairing modes near closed shells ➔ Phonons

\[ < f \mid T \mid i > ^2 \propto \frac{1}{\hbar \omega} \]

\[ \sigma_1 / \sigma_0 \approx \frac{\hbar \omega_0}{\hbar \omega_1} \]

\[ \sigma(n \rightarrow n+1) = (n+1)\sigma(0 \rightarrow 1) \]
Systematic of \((^3\text{He},p)\) and \((p,^3\text{He})\) N=Z nuclei

Single-particle estimate ~ \((\text{spin})x(^3\text{He})x(\text{LS} \rightarrow jj)\)
L=0 and $^1S_0$ Amplitude for a $j^2$ pair

Angular momentum
($^3\text{He},p$) Transfer Reactions in Reverse Kinematics
Measure $E(\Theta)$, $d\sigma/d\Omega (\Theta)$, $\sigma$ ~ 20 counts/day
\[ A=46 \quad (^{44}\text{Ti}, \ ^{3}\text{He}, p \rightarrow ^{46}\text{V}) \]
\[ f_{7/2}^4 \otimes p_{3/2}^2 \]

Counts

Proton Energy (10 keV)
Systematic of $({}^3\text{He},p)$ and $(p,{}^3\text{He})$ $N=Z$ nuclei

Single-particle estimate $\sim (\text{spin}) \cdot ({}^3\text{He}) \cdot (\text{LS} \rightarrow jj)$
Alpha-like quartets?
Isospin conservation and quarteting

\[ H = \sum_i \varepsilon_i (N_i^{(v)} + N_i^{(\pi)}) + \sum_{ij,\tau} V(i, j) P_{i,\tau}^+ P_{j,\tau} \]

\[ P_{i1}^+ \propto \nu_i^+ \nu_i^- \quad P_{i-1}^+ \propto \pi_i^+ \pi_i^- \quad P_{i0}^+ \propto \nu_i^+ \pi_i^- + \pi_i^+ \nu_i^- \]

**non-collective quartets**

\[ Q_{ij}^+ = [P_{i\tau}^+ P_{j\tau'}^+]^{T=0} \propto P_{v\nu,i}^+ P_{\pi\nu,j}^+ + P_{\pi\pi,i}^+ P_{\nu\nu,j}^+ - P_{v\pi,i}^+ P_{\nu\pi,j}^+ \]

**collective quartet**

\[ Q^+ = \sum_{ij} x_{ij} [P_{i\tau}^+ P_{j\tau'}^+]^{T=0} \]

**quartet condensate**

\[ |QCM \rangle \geq Q^{+n_q} |-\rangle \quad \text{(has } T=0, J=0\text{)} \]
Quartet condensation and Cooper pairs

\(| QCM >= Q^{+n_q} | - >\)

\(Q^+ = \sum_{ij} x_{ij} [P^+_{i\tau} P^+_{j\tau}]^{T=0}\)

\(Q^+ = 2\Gamma_{\nu\nu}^+ \Gamma_{\pi\pi}^+ - \Gamma_{\nu\pi}^+ \Gamma_{\nu\pi}^+\)

\(\Gamma^+ = \sum_i x_i P^+_{i,\tau}\) collective pairs

\(| QCM >= (2\Gamma_{\nu\nu}^+ \Gamma_{\pi\pi}^+ - \Gamma_{\nu\pi}^+ \Gamma_{\nu\pi}^+)^{n_q} | - >\)

'coherent' mixing of condensates formed by nn, pp and pn pairs

\(| PBCS0 > \propto (\Gamma_{\nu\tau}^{+2})^{n_q} | - >\)
\(| PBCS1 > \propto (\Gamma_{\nu\nu}^+ \Gamma_{\pi\pi}^+)^{n_q} | - >\)

calculations

\(\delta_x < QCM | H | QCM >= 0\)

method of recurrence relations
Quartet condensation versus pair condensation

\[ H = \sum_i \varepsilon_i N_i + \sum_{ij} V_{ij=0}^{T=1}(i,j) \sum_t P^+_i P^+_j \]

pairing forces extracted from SM interactions

\[ |QCM > \equiv (Q^+)^n_q | - > \quad |PBCS1 > \propto (\Gamma^+ \Gamma^+)^n_q | - > \quad |PBCS0 > \propto (\Gamma^+)^{\nu^2}_q | - > \]

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>QCM</th>
<th>PBCS1</th>
<th>PBCS0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}$Ne</td>
<td>9.173</td>
<td>9.170 (0.033%)</td>
<td>8.385 (8.590%)</td>
<td>7.413 (19.187%)</td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>14.460</td>
<td>14.436 (0.166%)</td>
<td>13.250 (8.368%)</td>
<td>11.801 (18.389%)</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>15.787</td>
<td>15.728 (0.374%)</td>
<td>14.531 (7.956%)</td>
<td>13.102 (17.008%)</td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>15.844</td>
<td>15.795 (0.309%)</td>
<td>14.908 (5.908%)</td>
<td>13.881 (12.389%)</td>
</tr>
<tr>
<td>$^{44}$Ti</td>
<td>5.973</td>
<td>5.964 (0.151%)</td>
<td>5.487 (8.134%)</td>
<td>4.912 (17.763%)</td>
</tr>
<tr>
<td>$^{48}$Cr</td>
<td>9.593</td>
<td>9.569 (0.250%)</td>
<td>8.799 (8.277%)</td>
<td>7.885 (17.805%)</td>
</tr>
<tr>
<td>$^{52}$Fe</td>
<td>10.768</td>
<td>10.710 (0.539%)</td>
<td>9.815 (8.850%)</td>
<td>8.585 (20.273%)</td>
</tr>
<tr>
<td>$^{100}$Te</td>
<td>3.831</td>
<td>3.829 (0.052%)</td>
<td>3.607 (5.847%)</td>
<td>3.356 (12.399%)</td>
</tr>
<tr>
<td>$^{108}$Xe</td>
<td>6.752</td>
<td>6.696 (0.829%)</td>
<td>6.311 (6.531%)</td>
<td>5.877 (12.959%)</td>
</tr>
<tr>
<td>$^{112}$Ba</td>
<td>8.680</td>
<td>8.593 (1.002%)</td>
<td>8.101 (6.670%)</td>
<td>13.064 (13.064%)</td>
</tr>
</tbody>
</table>

Conclusions

- $T=1$ pairing is accurately described by quartets, not by pairs
- there is not a pure condensate of isovector pn pairs in N=Z nuclei

Alpha-like quartetting versus alpha clustering

unified microscopic treatment?

Quartetting  Alpha-clustering  Alpha condensation?

ground state  excited states  Hoyle state in $^{12}\text{C}$?

Ab initio Monte Carlo calculations in light N=Z nuclei

ground state of N=Z nuclei are close to a phase transition between an alpha boson condensate and a quantum liquid

Testing alpha-like quartet condensation in N=Z nuclei?

- test of quartet condensation
  
  $$< QCM(A+4) | Q^+ | QCM(A) > \quad \quad | QCM > \equiv (Q^+)^{n_q} | - >$$

$^{16}O \xrightarrow{\alpha} ^{20}Ne \xrightarrow{\alpha} ^{24}Mg \xrightarrow{\alpha} ^{28}Si \xrightarrow{\alpha} ^{32}S$

experiments for heavier N=Z nuclei (ph-shell)?
Next Steps

$^{48}\text{Cr}, \, ^{56}\text{Ni}$  GANIL MUST2 + EXOGAM  
M. Assie et al.

(p,$^3\text{He}$), ($^3\text{He}$,p) and (d,$^\alpha$) reactions

LOI for ReA3 at NSCL using the AT-TPC  
LBNL, NSCL

LOI for HIE ISOLDE  
D. Jenkins et al.

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(t,p) , (p,t) , charge exchange, and one-nucleon transfer:  (d,p), ($^3\text{He}$,d), ....

(d,$^6\text{Li}$) , ($^6\text{Li}$,d), ($^{12}\text{C}$, $^8\text{Be}$)  quartet
Next Steps

Reaccelerated N=Z beams

Rates (pps)

A

Normal
Superfluids
Normal
Fast beams
ReA3
Spiral2

Simple Setup
HELIOS
AT-TPC
Should we consider *np* knockout reactions?
Even-even $T=0 \ J=0$

Odd-odd $T=1 \ J=0$

KO to lowest $J_{\pi}=0^+, 1^+$

Exclusive measurement - Cross section and momentum distribution

Conceptually simple, technically challenging !!
Qualitative Form-Factor for the KO of an L=0 pair

(\( N, \Lambda \ n, \lambda \))

\[ R \ (\text{fm}) \]

\[ (1,1 \ 1,1) \quad (2,0 \ 1,0) \quad (2,1 \ 0,1) \quad (3,0 \ 0,0) \]

\[ \Rightarrow \ S- \text{ and } P- \text{ waves} \]
Partial-wave contributions to pairing in nuclei

Simone Baroni, Augustine O. Macchiavelli, and Achim Schwenk
$f_{7/2}$ Schiffer-True interaction oscillator parameter $= 0.26$ fm$^{-1}$
\((N, \Lambda, n, \lambda)\)
Short-range Correlations
Beyond mean field

Short Range correlations

“Dressed” quasi-nucleons

Tensor force

Jefferson Laboratory

upgrade existing halls

Tante Grazie !