New Properties of High Momentum Distribution of Nucleons in Asymmetric Nuclei.

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Based on the recent experimental observations of the dominance of tensor interaction in the 
\( \sim 250-600 \text{ MeV/c} \) momentum range of nucleons in nuclei, the existence of two new properties for
high-momentum distribution of nucleons in asymmetric nuclei is suggested. The first property is the
approximate scaling relation between proton and neutron high-momentum distributions weighted
by their relative fractions in the nucleus. The second property is the inverse proportionality of the
strength of the high-momentum distribution of protons and neutrons to the same relative fractions.
Based on these two properties the high-momentum distribution function for asymmetric nuclei has
been modeled and demonstrated that it describes reasonably well the high-momentum characteristics
of light nuclei. However, the most surprising result is obtained for neutron rich nuclei with large
\( A \), for which a substantial relative abundance of high-momentum protons as compared to neutrons
is predicted. For example, the model predicts that in Au the relative fraction of protons with
momenta above \( k_F \sim 260 \text{ MeV/c} \) is 50% more than that of neutrons. Such a situation may have
many implications for different observations in nuclear physics related to the properties of a proton
in neutron rich nuclei.

I. INTRODUCTION

One of the exciting recent results in the studies of
short-range properties of nuclei is the observation of
the strong (by factor of 20) dominance of the \( \text{pn} \) short
range correlations (SRCs) in nuclei, as compared to \( pp \) and
\( nn \) correlations, for internal momenta of \( \sim 250 -
600 \text{ MeV/c} \) [1, 2]. This observation is understood [1, 2, 4]
based on the dominance of the tensor forces in the NN
interaction at this momentum range corresponding to av-
erage nucleon separations of \( \sim 1.1 \text{ Fm} \). The tensor in-
teraction projects the NN SRC part of the wave function
into the isosinglet - relative angular momentum, \( L = 2 \)
state, almost identical to the \( D \)-wave component of the
deuteron wave function. At the same time, \( pp \) and \( nn \)
components of the NN SRC will be strongly suppressed
since they are dominated by the central NN potential
with relative \( L = 0 \).

In this work we explore the implication of the above ob-
servation on the properties of high momentum distribu-
tion of nucleons in asymmetric nuclei. Two new features are predicted: first, that high momentum distributions
of the proton and neutron weighted by their relative frac-
tions are approximately equal (Sec III) ; and second, for
moderately asymmetric nuclei the high momentum dis-
tribution of nucleon is inverse proportional to its fraction
in the nucleus (Sec IV). In Sec. V we demonstrate that
these properties predict strikingly different high momen-
tum tails for proton and neutron in neutron reach nuclei
such as Gold. Section VI discusses the results of real-
istic calculations for light nuclei (up to \( ^{11}B \)) which are
in reasonable agreement with the predicted properties of
high momentum distribution. Furthermore, in Sec. VII,
we discuss the possibilities of verification of the same
properties for heavy, neutron rich, nuclei through the
probing the high momentum distribution of nucleons in
semi-inclusive electro-nuclear reactions. Section VIII dis-
cusses the restrictions of the model and the accuracy of
the predictions. We then discuss (Sec. IX) the possible
implications of the new properties in different nuclear
phenomena such as isospin dependence of the medium
modification effects and properties of the proton in high
density nuclear matter. This section also addresses the
question of universality of the predicted features for any
asymmetric two-component Fermi system controlled only
by short range interaction between the components. The
conclusions are given in Sec. X.

II. HIGH MOMENTUM DISTRIBUTION OF
NUCLEONS IN NUCLEI AND 2N SRCs

Due to the short-range nature of strong interactions,
the property of an A-nucleon bound state wave func-
tion, in which one of the nucleons has momentum \( p \), such
that \( p^2 \gg |E_B| \) (binding energy), is defined mainly by
the 2N interaction potential \( V_N(N) \) at relative momenta
\( k \sim p \), i.e.: \( \Psi_A(p,p_2,p_3,\cdots p_A) \sim \frac{V_N(k)}{k^2} f(p_1,\cdots p_A) \),
where \( p_2 \approx -\vec{p} \approx -\vec{k} \) and \( f(\cdots) \) is a smooth func-
tion of the momenta of non-correlated nucleons[5, 7].
This result follows from a dimensional analysis of the
Lipmann-Schwinger type equations for A-nucleon system
described by NN potential which decreases at large \( k \) as
\( V(k) \sim \frac{1}{kn} \), with \( n > 1 \). This asymptotic form of the
wave function leads to the approximate relation for nu-
cleon momentum distribution at \( p > k_F \), with \( k_F \) being
the characteristic Fermi momentum of the nucleus:
\[
n_A^{A}(p) \sim a_{NN}(A) \cdot n_{NN}(p)
\]
where the full momentum distribution is normalized as
\( \int n_A^{A}(p)d^3p = 1 \). The parameter \( a_{NN}(A) \) can be inter-
preted as a probability of finding NN SRC in the given
nucleus \( A \). The function, \( n_{NN}(p) \) is the momentum dis-
tribution in the NN SRC [5, 6, 8, 11], where NN represents
the combination of all possible isospin pairs.
If, following the above discussed dominance of tensor interactions, we neglect the contributions from \( pp \) and \( nn \) SRCs, one expects that in the range of \( \sim k_F - 600 \text{ MeV}/c \) the momentum distribution in the NN SRC is defined by \( pn \) correlations only. Using this and the local nature of SRCs one predicts:

\[
n_{NN}(p) \approx n_{pn}(p) \approx n_d(p),
\]

where \( n_d(p) \) is the deuteron momentum distribution.

For further discussion we introduce the individual momentum distributions of proton (\( n^A_p(p) \)) and neutron (\( n^A_n(p) \)) such that:

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

and \( \int n^A_{p/n}(p) d^3p = 1 \). Here the two terms in the sum represent the probability density of finding in the nucleus a proton or neutron with momentum \( p \).

### III. APPROXIMATE SCALING RELATION

Integrating Eq. (3) within the momentum range of NN SRCs one observes that the terms in the sum give the total probabilities of finding a proton and a neutron in the NN SRC. Since the SRCs within our approximation consist only of the \( pn \)-pairs, the total probabilities of finding proton and neutron in the SRC are equal This is the reflection of the fact that in our approximation no other possibilities exist for NN SRCs. Furthermore within the approximation in which one neglects the center of mass motion of the \( pn \) SRCs one can make a stronger statement on the equality of integrands of the above integrals, i.e. in \( \sim k_F - 600 \text{ MeV}/c \) region:

\[
x_p \cdot n^A_p(p) \approx x_n \cdot n^A_n(p),
\]

where \( x_p \approx \frac{Z}{A} \), \( x_n = \frac{A-Z}{A} \). This represents the first property, according to which the momentum distributions of proton and neutron weighted by their respective fractions are approximately equal.

### IV. FRACTIONAL DEPENDENCE OF HIGH MOMENTUM COMPONENTS

Using the high momentum relations of (1) and (2) for \( n^A(p) \) and the relation (3) in Eq. (3) one obtains in \( \sim k_F - 600 \text{ MeV}/c \) momentum range

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

where \( a_{NN}(A) \approx a_{pn}(A, y) \equiv a_2(A, y) \) and the nuclear asymmetry parameter is defined as \( y = |x_n - x_p| \).

Within the approximation in which only \( pn \) SRCs are included the parameter \( a_2(A, y) \) satisfies to two limiting conditions: (i) \( a_2(A, 0) \) is defined only by the nuclear density; and (ii) \( a_2(A, 1) = 0 \) due to the neglect of \( pp \) and \( nn \) SRCs. This allows us to represent \( a_2(A, y) \) as:

\[
a_2(A, y) = a_2(A, 0) \left[ 1 - \sum_{j=1}^{n} b_j |x_n - x_p|^j \right],
\]

with the condition \( \sum_{j=1}^{n} b_j = 1 \) to satisfy the limiting condition (ii). The latter relation indicates that it is always possible to satisfy an inequality: \( \sum_{j=1}^{n} b_j |x_n - x_p|^j \ll 1 \) in which case one can formulate the second property of the high momentum distribution: that, according to Eq. (5), the probability of proton or neutron being in high momentum NN correlation is inverse proportional to their relative fractions (\( x_p \) or \( x_n \)) in the nucleus.

### V. RELATIVE NUMBER OF HIGH MOMENTUM PROTONS AND NEUTRONS

The most important prediction that follows from the second property is that the relative number of high momentum protons and neutrons became increasingly unbalanced with an increase of the nuclear asymmetry, \( y \).

To quantify this prediction, using Eq. (5) one can calculate the fraction of the nucleons having momenta \( \geq k_F \) as:

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

where we extended the upper limit of integration to infinity assuming smaller overall contribution from the momentum range of \( \geq 600 \text{ MeV}/c \). The results of the calculation of these fractions for medium to heavy nuclei, using the estimates of \( a_2(A, y) \) from Ref. [10–14] and \( k_F \) from Ref. [15] are given in Table I. As it follows from the table with the increase of the asymmetry the imbalance between the high momentum fractions of proton and neutron grows. For example, in the Gold, the relative fraction of high momentum (\( \geq k_F \)) protons is 50% more than that of the neutrons.

\[
\begin{array}{cccc|cccc}
A & P_p(\%) & P_n(\%) & A & P_p(\%) & P_n(\%) \\
\hline
12 & 20 & 56 & 27 & 22 & 197 & 31 & 23
\end{array}
\]
VI. HIGH MOMENTUM FEATURES OF LIGHT NUCLEI

One can check the validity of the above two (Eqs. (4) and (5)) observations for light nuclei for which it is possible to perform realistic calculations based on the Faddeev equations for $A=3$ systems[16]. Correlated Gaussian Basis(CGB) approach[17] as well as Variational Monte Carlo method(VMC)[19] for light nuclei $A$ (recently being available for up to $A=12$[18][20]).

First, we check the validity of Eq.(4) which is presented in Fig.[1] for $^3He$ nucleus, based on the solution of Faddeev equation[16], and for $^{10}Be$ based on VMC calculations[19]. In both cases the Argonne V18[21] potential is used for NN interaction. The solid lines with and without squares in Fig.1(a) represent neutron and proton momentum distributions for both nuclei weighted by their respective $x_n$ and $x_p$ factors.

![Figure 1](color online) (a) The momentum distributions of proton and neutron weighted by $x_p$ and $x_n$ respectively. The dotted lines represent the prediction for the momentum distribution according to Eq.(4). (b) The $x_p/x_n$ weighted ratio of neutron to proton momentum distributions. See the text for details.

As one can see for $^3He$, the proton momentum distribution dominates the neutron momentum distribution at small momenta reflecting the fact that in the mean field the probability of finding proton is larger than neutron just because there are twice as much protons in $^3He$. The same is true for $^{10}Be$ for which now the neutron momentum distribution dominates at small momenta. However at $\sim 300$ MeV/c for both nuclei, the proton and neutron momentum distributions become close to each other up to the internal momenta of 600MeV/c. This is the region dominated by tensor interaction.

This effect is more visible for the ratios of weighted n- to p- momentum distributions in Fig.1(b), demonstrating that the approximation of Eq.(4) in the range of 300 – 600 MeV/c is good on the level of 15%. Note that the similar features present for all other asymmetric nuclei calculated within the VMC method in Ref.[18][20].

Next, we check the the validity of Eq.(5). For this we use the estimates of $\alpha_2$ for $^3He$ and $^{10}Be$ from Refs.[14][17] and the deuteron momentum distribution $n_d$ calculated using the same Argonne V18 NN potential[21]. The calculations based on Eq.(5) are given by dotted lines in Fig.1(a). As it follows from these comparisons, the model of Eq.(5) works rather well starting at 200 MeV/c up to the very large momenta $\sim 1$ GeV/c. This reflects the fact that the center of mass motion effects and higher partial waves in 2N- as well as 3N- SRCs are not dominant in light nuclei.

The final prediction which we check is the one following from Eq.(7) according to which the smallest component should be more energetic in the asymmetric nuclei. Namely, one expects more energetic neutron than proton in $^3He$ and the opposite result for neutron rich nuclei. This expectation is confirmed for $p-$ and $n-$ kinetic energies of all nuclei calculated within Faddeev equation, CGB approach and VMC method (see Table II).

Thus we conclude that all the observations concerning the features of high momentum distribution in asymmetric nuclei are in reasonable agreement with the results following from the realistic wave functions of light nuclei.

![Table II](Kinetic energies (in MeV) of proton and neutron)

| $^A$Be  | $y$ | $E_{kin}^p$ | $E_{kin}^n$ | $E_{kin}^p - E_{kin}^n$ |
|-------|---|----------|----------|-------------------|
| $^8He$ | 0.50 | 30.13 | 18.60 | 11.53 |
| $^6He$ | 0.33 | 27.66 | 19.06 | 8.60 |
| $^9Li$ | 0.33 | 31.39 | 24.91 | 6.48 |
| $^3He$ | 0.33 | 14.71 | 19.35 | -4.64 |
| $^3He$ | 0.33 | 13.70 | 18.40 | -4.7 |
| $^3He$ | 0.33 | 13.97 | 18.74 | -4.8 |
| $^3H$ | 0.33 | 19.61 | 14.96 | 4.65 |
| $^8Li$ | 0.25 | 28.95 | 23.98 | 4.97 |
| $^{10}Be$ | 0.2 | 30.20 | 25.95 | 4.25 |
| $^7Li$ | 0.14 | 26.88 | 24.54 | 2.34 |
| $^9Be$ | 0.11 | 29.82 | 27.09 | 2.73 |
| $^{11}B$ | 0.09 | 33.40 | 31.75 | 1.65 |

VII. HIGH MOMENTUM FEATURES OF HEAVY NUCLEI

Presently, no ab-initio calculations exist for heavy nuclei for the predictions of Eqs. (4) and (5) to be checked. However, these properties can be checked experimentally.
in semi-inclusive nucleon knock-out $A(e,e'N)X$ reactions on asymmetric nuclei in which the momentum distribution of the nucleon can be probed if final state interactions (FSI) are in control. Such a control can be achieved at large $Q^2 > 1$ GeV$^2$ kinematics in which case it was demonstrated that the FSI effects can be estimated reasonably well within eikonal approximation (see e.g. [22] and references therein). The first such experimental verification for heavy nuclei is currently underway in quasi-elastic $A(e,e,p)X$ measurement at Jefferson Lab, where the ratio of high momentum fractions of nucleons in $^{56}$Fe and $^{208}$Pb to that of $^{12}$C is extracted. The results [23] are in reasonably good agreement with the prediction of Eq.(7) (Table 1) and they are currently being prepared for publication.

It is worth noting that there is a possibility of designing a host of new $(e,e'N)$ experiments with asymmetric nuclei at specific kinematics in which $x_{Bjorken} > 1$ and

\[ |p_m| - q_0 \left( E_m + \frac{p_m^2}{2M_{A-1}} \right) > k_F, \]

where $p_m$, $E_m$, $q_0$ and $q_v$ are missing momentum, missing energy, transferred energy and transferred momentum in the reaction (see e.g. Ref. [24] for details) in which case it is possible to extract the high momentum distribution of nucleons with minimal distortion due to FSI effects. Such measurements will allow to check also the predictions of Eqs.(1) and (5). Moreover the $(e,e'N)$ experiments will allow to extract nuclear spectral functions which contain additional information on the structure of SRCs, such as correlation between missing energy and missing momentum. One of the first measurements [20] of the nuclear spectral function at SRC region confirmed the high potential of the $(e,e'N)$ reactions in correlation studies.

VIII. RESTRICTION OF THE MODEL:

In the above made observations we neglected the $pp$ and $nn$ SRCs which are present in non-tensor (e.g. $S=0$-state) as well as the $T = 1$, $S = 1$ part of the NN interactions. These contributions are expected to increase with A. We also neglected the C.M. motion of $pn$ SRCs. It is rather well established that, for $A \geq 12$, in the momentum range of $k_F < p < 600$ MeV/c the C.M. momentum of the NN SRC has distribution with the width being proportional to $k_F$ [27, 31]. Thus one expects the accuracy of the observed relations (1) and (5) to be worsen with increase of A.

However, due to the mean field character of the C.M. motion as well as the equal contributions of the $pp$ and $nn$ SRCs to the overall strength of the NN correlations one expects the validity of modified relation:

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

where $\gamma \equiv \gamma(k_F) \lesssim 1$, with $\gamma$ decreasing with an increase of $A$ (or $k_F$). The same $\gamma$ factor will enter also in the high momentum part of the momentum distribution of the protons and neutrons

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

which will diminish the imbalance between high momentum protons and neutrons presented in Table 1.

Very recently, the above predictions have been checked for momentum distributions of asymmetric infinite nuclear matter at above saturation densities calculated within Green function method [28, 29]. These calculations observe the scaling of the weighted ratios of the high momentum parts of the proton and neutron momentum distributions and indicate that the power law scaling behavior of Eq.(5) valid for moderate asymmetries. This and the above discussed experimental measurements of $^{56}$Fe and $^{208}$Pb are the first indications that predictions of Eqs. (4, 9) may have validity for heavy nuclei and infinite nuclear matter.

Overall, the realistic nuclear structure calculations that can systematically incorporate short range correlations for asymmetric nuclei (see e.g. [23, 30]) combined with experimental studies of $A(e,e'N)X$ reactions will allow to check the predictions of Eqs. (8, 9) as well as evaluate the $\gamma$ factor as a function of nuclear parameters.

IX. POSSIBLE IMPLICATIONS AND UNIVERSALITY OF THE PREDICTED FEATURES FOR TWO-COMPONENT FERMI SYSTEMS

The implications of the above made observations could range from the EMC effects to the proton properties in high density asymmetric nuclear matter. These observations suggest several new directions in studies of the high momentum component of asymmetric nuclei.

- For example; combining three following observations: (i) nuclear medium modification (EMC effect) of parton distribution functions (PDFs) are proportional to the virtuality (momentum) of the bound nucleon (see e.g. 9, 32, 33); (ii) high momentum protons dominate in neutron rich nuclei (this article) and; (iii) PDFs of proton dominate that of the neutron at $x_{Bjorken} \geq 0.3$ (see e.g. 35), one can conclude that the EMC effects for neutron rich nuclei will be defined mainly by the proton component in the nucleus. This may explain the large A part of the recently observed correlation between the strengths of the EMC and SRC effects [37, 38].

- The prediction of the enhanced contribution of protons in the EMC effect indicates that in average the $u$-quarks will be more modified than $d$-quarks in neutron rich nuclei and the effect will grow with A. This provides an alternative explanation of the NuTeV anomaly [40, 41]. The predicted effect also can be checked in parity violating deep inelastic scattering off the heavy nuclei.

- The discussed new features of the high momentum component of nucleon momentum distributions could be
relevant also for high density asymmetric nuclear matter. In Ref. [13] such a possibility is discussed for neutron stars at the cooling threshold of direct neutrino scattering (referred to as URCA processes) with $x_p \sim \frac{1}{3}$ and $y \sim \frac{1}{2}$. For example it is observed [14,12] that if the above made observations are valid for infinite nuclear matter then starting at three nuclear saturation densities, protons will predominantly populate the high momentum part of the momentum distribution. This may have an implication for several properties of neutron stars such as cooling through the direct URCA processes, superfluidity of protons, the magnetic field of the stars as well as the distribution of protons in the core of the massive neutron stars.

Our observations in this work follow from two main general conditions: First, that the interaction is short range and in high momentum limit the multiparticle wave function can be factorized to NN correlated and A-2 mean field components. Second: the pn interaction significantly dominates that of the pp and nn interactions.

As such, the present results may have a relevance to any asymmetric two-component Fermi system for which above two conditions are satisfied: that is the interaction within each component is suppressed while the mutual interaction between two components is finite and short range. In such a situation, according to our observations the momentum distribution of the small component will be shifted to the high momentum part of the distribution.

It is interesting that the similar situation potentially can be realized in two-fermi-component ultracold atomic systems [13] but with the mutual s-state interaction. One of the most intriguing aspects of such systems is that in the large asymmetric limit they exhibit very rich phase structure with indication of the strong modification of the small component of the mixture [14,15]. In this respect our case may be similar to that of ultracold atomic systems, with the difference that the interaction between components has a tensor nature.

X. SUMMARY AND CONCLUSIONS:

Based on the dominance of the tensor forces in the NN system for the momentum range of $\sim k_F - 600\text{MeV}/c$ we observe a new scaling relation between $p$- and $n$- high momentum distributions weighted by their fractions in the nuclei (Eq. [4]). Using this, together with their relation to the high momentum distribution of the deuteron we arrive at the second observation, according to which the strengths of the $p$- and $n$- high momentum components are inversely proportional to their relative fractions. Based on these observations we constructed the $p$- and $n$- high momentum distributions for asymmetric nuclei and estimated the overall fraction of nucleons being in the high momentum part of the momentum distribution.

The validity of our observations for light nuclei are confirmed by direct calculations using realistic wave functions. The first experimental measurements for large A nuclei and calculations for infinite nuclear matter indicate the relevance of the predictions also for heavy nuclei and nuclear matter.

We also observe that the effects due to center of mass motion of NN SRCs as well as contributions from pp and nn SRCs will diminish the estimated imbalance between high momentum protons and neutrons for large A nuclei. If this imbalance will be observed for heavy nuclei and infinite nuclear matter it will have multitude of implications, some of which we discussed in the text.

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