New properties of the 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 ~250–600 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 so 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 $k_F \sim 260$ 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.

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I. INTRODUCTION

One of the exciting recent results in the studies of short-range properties of nuclei is the observation of the strong (by a factor of 20) dominance of the pn short-range correlations (SRCs) in nuclei, as compared to pp and nn correlations, for internal momenta of ~250–600 MeV/c [1,2]. This observation is understood [1,3,4] based on the dominance of the tensor forces in the NN interaction at this momentum range corresponding to average nucleon separations of ~1.1 Fm. The tensor interaction 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, the 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 the implication of the above observation on the properties of high-momentum distribution of nucleons in asymmetric nuclei is explored. Two new features are predicted: *first*, that high-momentum distributions of the proton and neutron weighted by their relative fractions are approximately equal (Sec III) and *second*, for moderately asymmetric nuclei the high-momentum distribution of the nucleon is inverse proportional to its fraction in the nucleus (Sec IV). In Sec. V it is demonstrated that these properties predict strikingly different high-momentum tails for a proton and neutron in neutron-rich nuclei such as Au. Section VI discusses the results of realistic calculations for light nuclei (up to ^{11}B), which are in reasonable agreement with the predicted properties of the high-momentum distribution. Furthermore, in Sec. VII, the possibilities of the verification of the same properties for heavy neutron-rich nuclei are discussed through probing the high-momentum distribution of nucleons in semi-inclusive electronuclear reactions. Section VIII discusses the restrictions of the model and the accuracy of the predictions. Section IX discusses the possible implications of the new properties in different nuclear phenomena such as the isospin dependence of the medium modification effects and properties of the proton in high density nuclear matter. This section also addresses the question of the 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 function, in which one of the nucleons has momentum p, such that $\frac{p^2}{2m_N} \gg |E_B|$ (binding energy), is defined mainly by the 2N interaction potential (V_{NN}) at relative momenta $k \sim p$, i.e., $\Psi_A(p, p_2, p_3, \dots, p_A) \sim \frac{V_{NN}(k)}{k^2} f(p_3, \dots, p_A)$, where $\vec{p}_2 \approx -\vec{p} \approx -\vec{k}$ and $f(\cdots)$ is a smooth function of the momenta of noncorrelated nucleons [5–7]. This result follows from a dimensional analysis of the Lipmann-Schwinger-type equations for the A-nucleon system described by the NN potential, which decreases at large k as $V(k) \sim \frac{1}{k^n}$, with $n > 1$ [5,6]. This asymptotic form of the wave function leads to the approximate relation for nucleon momentum distribution at $p > k_F$, with k_F being the characteristic Fermi momentum of the nucleus

$$n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p), \tag{1}$$

where the full momentum distribution is normalized as $\int n^A(p) d^3p = 1$. The parameter $a_{NN}(A)$ can be interpreted as a probability of finding NN SRC in the given nucleus A. The function $n_{NN}(p)$ is the momentum distribution in the NN SRC [5,6,8–10], where NN represents the combination of all possible isospin pairs.

If, following the above-discussed dominance of tensor interactions, the contributions from pp and nn SRCs are neglected, then one expects that in the range of ~k_F–600 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

$$n_{NN}(p) \approx n_{pn}(p) \approx n_d(p), \tag{2}$$

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

For further discussion the individual momentum distributions of the proton ($n_p^A(p)$) and neutron ($n_n^A(p)$) are introduced such that

$$n^A(p) = \frac{Z}{A} n_p^A(p) + \frac{A-Z}{A} n_n^A(p) \tag{3}$$

and $\int n_{p/n}^A(p) d^3p = 1$. 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 a 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 the $\sim k_F$–600 MeV/c region

$$x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p), \tag{4}$$

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

IV. FRACTIONAL DEPENDENCE OF HIGH-MOMENTUM COMPONENTS

Using the high-momentum relations of Eqs. (1) and (2) for $n^A(p)$ and the relation (4) in Eq. (3) one obtains that in the $\sim k_F$–600 MeV/c momentum range

$$n_{p/n}^A(p) \approx \frac{1}{2x_{p/n}} a_2(A,y) \cdot n_d(p), \tag{5}$$

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 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

$$a_2(A,y) = a_2(A,0)\left[1 - \sum_{j=1}^{n} b_j \mid x_n - x_p \mid^j\right], \tag{6}$$

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 $\sum_{j=1}^n b_j \mid x_n - x_p \mid^j \ll 1$, in which case one can formulate the *second* property of the high-momentum distribution: that, according to Eq. (5), the probability of a proton or neutron being in high momentum NN correlation is inverse proportional to their relative fractions (x_p or x_n) in the nucleus.

TABLE I. Fractions of high-momentum protons and neutrons in nuclei A.

A	$P_p(\%)$	$P_n(\%)$	A	$P_p(\%)$	$P_n(\%)$
12	20	20	56	27	23
27	24	22	197	31	20

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 $\geqslant k_F$ as

$$P_{p/n}(A,y) \approx \frac{1}{2x_{p/n}} a_2(A,y) \int_{k_F}^{\infty} n_d(p) d^3p, \tag{7}$$

where the upper limit of integration is extended to infinity assuming a smaller overall contribution from the momentum range of $\geqslant$600 MeV/c. The results of the calculation of these fractions for medium to heavy nuclei, using the estimates of $a_2(A,y)$ from Refs. [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 the proton and neutron grows. For example, in Au, the relative fraction of high-momentum ($\geqslant k_F$) protons is 50% more than that of the neutrons.

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 the variational Monte Carlo method (VMC) [18] for light nuclei A (recently available for up to $A = 12$ [19,20]).

First, the validity of Eq. (4) is checked, which is presented in Fig. 1 for the ^{3}He nucleus, based on the solution of the Faddeev equation [16], and for ^{10}Be based on VMC calculations [18]. In both cases the Argonne V18 [21] potential is used for the 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.

As one can see for ^{3}He, the proton momentum distribution dominates the neutron momentum distribution at small momenta reflecting the fact that in the mean field the probability of finding the proton is larger than the neutron just because there are twice as many protons in ^{3}He. 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

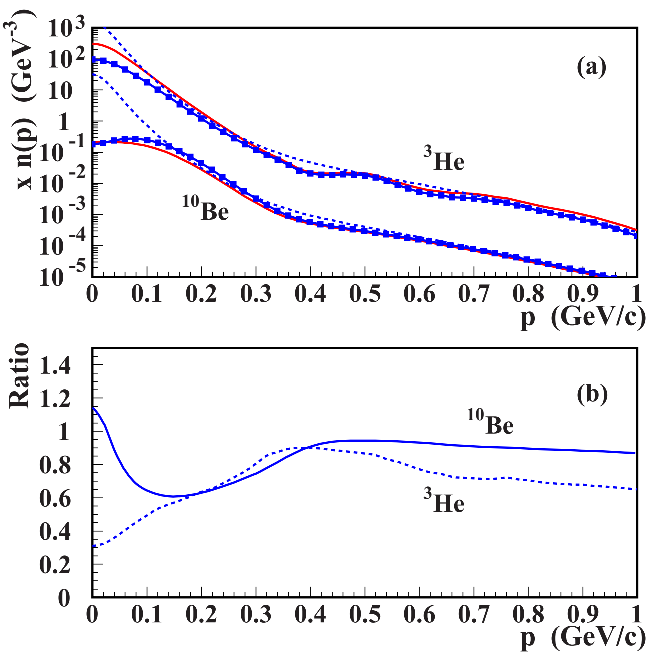

FIG. 1. (Color online) (a) The momentum distributions of a proton and neutron weighted by x_p and x_n, respectively. The doted lines represent the prediction for the momentum distribution according to Eq. (5). (b) The $x_{p/n}$ weighted ratio of neutron to proton momentum distributions. See the text for details.

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 were calculated within the VMC method found in Refs. [19,20].

Next, the validity of Eq. (5) is checked. For this the estimates of a_2 for ^{3}He and ^{10}Be from Refs. [13,14] are used 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 the doted 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 ~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 to be checked is the one following from Eq. (7) according to which the smallest component should be more energetic in the asymmetric nuclei. Namely, one expects a more energetic neutron than proton in ^{3}He and the opposite result for neutron-rich nuclei. This expectation is confirmed for p and n kinetic energies of all nuclei calculated within the Faddeev equation, CGB approach, and VMC method (see Table II).

Thus one concludes that all the observations concerning the features of a 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 a proton and neutron.

A	y	$E^p_{\rm kin}$	$E^n_{\rm kin}$	$E^p_{\rm kin} - E^n_{\rm kin}$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	−4.64
^{3}He [16]	0.33	13.70	18.40	−4.7
^{3}He [17]	0.33	13.97	18.74	−4.8
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	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 the eikonal approximation (see, e.g., Ref. [22] and references therein). The first such experimental verification for heavy nuclei is currently underway in a quasielastic $A(e,e,p)X$ measurement at the Jefferson Laboratory, 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 I) 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 $x_{\rm Bjorken} > 1$ and $|p^z_m| - \frac{q_0}{q_v}(E_m + \frac{p_m^2}{2M_{A-1}}) > k_F$, where p_m, E_m, q_0, and q_v are the missing momentum, missing energy, transferred energy, and transferred momentum in the reaction (see, e.g., Refs. [24,25] 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. (4) 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 the correlation between the missing energy and missing momentum. One of the first measurements [26] of the nuclear spectral function at the SRC region confirmed the high potential of the $(e,e'N)$ reactions in correlation studies.

VIII. RESTRICTION OF THE MODEL

The pp and pn SRCs which are neglected in the above mentioned observations are present in nontensor (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. Also neglected is the center of mass (c.m.) motion of pn SRCs. It is rather well established that, for $A \geqslant 12$, in the momentum range of $k_F < p < 600$ MeV/c the c.m. momentum of the NN SRC has a distribution with the width being proportional to k_F [7,27,28]. Thus one expects the accuracy of the observed relations [Eqs. (4) and (5)] to worsen with the 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 the modified relation

$$x_p^\gamma \cdot n_p^A(p) \approx x_n^\gamma \cdot n_n^A(p), \tag{8}$$

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

$$n_{p/n}^A(p) \approx \frac{1}{(2x_{p/n})^\gamma} a_2(A,y) \cdot n_d(p), \tag{9}$$

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

Very recently, the above predictions have been checked for momentum distributions of asymmetric infinite nuclear matter at above-saturation densities calculated within the Green's function method [29,30]. These calculations observed the scaling of the weighted ratios of the high-momentum parts of the proton and neutron momentum distributions and indicated that the power-law scaling behavior of Eq. (8) was valid for moderate asymmetries. This and the above-discussed experimental measurements of ^{56}Fe and ^{208}Pb are the first indications that the predictions of Eqs. (4) and (5) or Eqs. (8) and (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., Refs. [29,31]) combined with the experimental studies of $A(e,e'n)X$ reactions will allow to check the predictions of Eqs. (8) and (9) as well as evaluate the γ 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 the 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., Refs. [9,32–34]); (ii) high-momentum protons dominate in neutron-rich nuclei (this article); and (iii) PDFs of a proton dominate that of the neutron at $x_{\rm Bjorken} \geqslant 0.3$ (see, e.g., Ref. [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 [36] 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 on average the u quarks will be more modified than the d quarks in neutron-rich nuclei and the effect will grow with A. This provides an alternative explanation [39] of the NuTeV anomaly [40,41]. The predicted effect also can be checked in parity violating deep inelastic scattering of 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. [14] such a possibility was discussed for neutron stars at the cooling threshold of direct neutrino scattering (referred to as URCA processes) with $x_p \sim \frac{1}{8}$ and $y \sim \frac{7}{9}$. For example, it was observed [14,42] that if the above-made observations were 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-ranged and in the 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 the above two conditions are satisfied; that is, the interaction within each component is suppressed while the mutual interaction between the two components is finite and short-ranged. 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 [43], 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 an indication of the strong modification of the small component of the mixture [44,45]. In this respect our case may be similar to that of ultracold atomic systems, with the difference being that the interaction between components has a tensor nature.

X. SUMMARY AND CONCLUSION

Based on the dominance of the tensor forces in the NN system for the momentum range of $\sim k_F$–600 MeV/c. A new scaling relations is observed 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, one arrives 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 the

p and n high-momentum distributions are constructed for asymmetric nuclei and the overall fraction of nucleons being in the high-momentum part of the momentum distribution are estimated.

The validity of these 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.

It is also observed that the effects due to the c.m. 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 is observed for heavy nuclei and infinite nuclear matter it will have a multitude of implications, some of which are discussed in the text.

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