A New Structure in the Deuteron

Misak M. Sargsian and Frank Vera
Florida International University, Miami, Florida 33199,USA

(Dated: August 22, 2022)

We demonstrate that a paradigm shift from considering the deuteron as a system of bound proton and neutron to considering it as a pseudo-vector system in which we observe proton and neutron, results in a possibility of probing a new "incomplete" P-state like structure on the light-front (LF), at extremely large internal momenta, which can be achieved in high energy transfer electro-disintegration of the deuteron. Investigating the deuteron on the light-front, where the vacuum-fluctuations are suppressed, we found that this new structure, together with conventional S- and D- states, is a leading order in transferred energy of the reaction, thus it is not suppressed on the light-front. The incompleteness of the observed P-state results in a violation of angular condition which can happen only if deuteron contains non-nucleonic structures such as $\Delta\Delta$, N^*N or hidden color components. We demonstrate that experimentally verifiable signatures of "incomplete" P-states are angular anisotropy of LF momentum distribution of the nucleon in the deuteron as well as an enhancement of the tensor polarization strength beyond the S- and D- wave predictions at large internal momenta in the deuteron.

One of the outstanding issues of strong interaction physics is the understanding of the dynamics of transition between hadronic to quark-gluon phases of matter. Such transitions at high temperature is relevant to the evolution of the universe after the big bang and can be studied experimentally in heavy ion collisions. Transitions at low (near zero) temperatures and high densities ("cold-dense" transitions) are relevant for superdense nuclear matter that can exists at the cores of neutron stars and can set up the limits of matter density before it collapses to the black hole. However the direct exploration of "cold-dense" transitions is severely restricted.

Currently the accepted ways of investigating such transitions are;

(1) Studying nuclear medium modification of quark-gluon structure of bound nucleons: Such a modification was discovered in 1983 - by European Muon Collaboration[1] - commonly referred to as EMC effect. Few progresses were made in understanding of this phenomena for past 40 years (for reviews see [2, 3]), including the observation of the dependence of the effect on local nuclear density[4] and the important role of short range nucleonic correlations in the EMC effect for medium to large nuclei[5, 6]. In all these cases the role of the hadronic to quark-gluon transition is not clearly understood.

(2) Studying the implications of the transition of baryonic matter to the quark matter in the cores of neutron stars. The situation with the existence of quark matter in the cores of Neutron Stars even more unclear than with the EMC effect. With the observation of unexpectedly large neutron star masses[7] ($\approx 2.08 M_\odot$) it was expected that if such stars would have radii, $R < 10$ km it will be indicative of large quark matter component in their cores. However observed radiuses for the large mass neutron stars are above $R \geq 12$ km (e.g. Ref.[8]).

While progress in advancing the studies of EMC effects is seen in performing new generation of experiments in which density of nuclear medium is controlled by tagging a recoil nucleon which is in short range correlation with the probed nucleon (e.g. Ref.[9]). The neutron star studies rely on improving of detection techniques that will allow to identify anomalously small size neutron stars.

In the present work we are suggesting a new method of studying baryon-quark transition using simplest known atomic nucleus, the deuteron.

Deuteron on the Light Front (LF): Our current mindset about deuteron is fully non-relativistic, within which, the observation that it has total spin, $J = 1$ and positive parity, P, together with the relation that for non-relativistic wave function, $P = (-1)^l$, one concludes that the deuteron consists of S- and D- partial waves for proton-neutron system.

However if we are interested in deuteron structure at internal momenta comparable with the nucleon rest mass then nonrelativistic framework is not valid and the problem is more fundamental, related to the description of a relativistic bound system. This situation is similar to the description of quark structure of nucleon in QCD in which case due to the small masses of u- and d- quarks the vacuum fluctuations may overshadow the composite structure of the nucleon (see e.g. Ref.[10]).

To discuss relativistic structure of the deuteron on needs to identify the process in which the deuteron structure is probed. In our case we consider high-momentum transfer electrodisintegration process:

$$e + d \rightarrow e' + p + n \tag{1}$$

in which one of the nucleons are struck by the incoming probe and the spectator nucleon is probed with momenta comparable to nucleon masses. If one can neglect (or remove) the effects related to final state interactions of two outgoing nucleons, then the above reaction at high Q^2, measures the probability of observing proton and neutron in the deuteron at very large relative momenta. In such a formulation the deuteron is not a composite system consisting of proton and neutron but it is a composite pseudo - vector ($J = 1,\ P = +$) "particle" from which one extracts proton and neutron. How such a proton and neutron are produced at such extremal conditions is related to the dynamical structure of LF deuteron wave function, which may include internal elastic $pn \to pn$ as well as inelastic $\Delta\Delta \to pn$, $N^*N \to pn$ or $N_cN_c \to pn$ transitions. Here, Δ and N^* denote Δ-isobar and N^* resonances, while N_c is a color octet baryonic state contributing to the hidden-color component in the deuteron.

The framework for calculation of reaction (1) in relativistic domain is LF approach (e.g. Ref.[11–16]) in which one introduces LF deuteron wave function in the form:

$$\psi_d^{\lambda_d}(\alpha_i, p_\perp, \lambda_1\lambda_2) = -\frac{\bar{u}(p_2,\lambda_2)\bar{u}(p_1,\lambda_1)\Gamma_d^\mu \chi_\mu^{\lambda_d}}{\frac{1}{2}(m_d^2 - 4\frac{m_N^2+p_\perp^2}{\alpha_i(2-\alpha_i)})\sqrt{2(2\pi)^3}}, \quad (2)$$

where $\alpha_i = 2\frac{p_{i+}}{p_{d+}}$, $(i = 1,2)$ and $\alpha_1 + \alpha_2 = 2$ are LF momentum fractions of two nucleons outgoing from deuteron that has four-momentum p_d^μ.

Absorbing the energy denominator into the vertex function and using crossing symmetry one obtains:

$$\psi_d^\mu(\alpha_i, p_\perp, \lambda_1, \lambda_2) = -\bar{u}(p_2,\lambda_2)\Gamma_d^\mu(k)\frac{(i\gamma_2\gamma_0)}{\sqrt{2}}\bar{u}(p_1,\lambda_1)^T$$
$$= -\sum_{\lambda_1'}\bar{u}(p_1,\lambda_1)\Gamma_d^\mu\gamma_5\frac{\epsilon_{\lambda_1,\lambda_1'}}{\sqrt{2}}u(p_1,\lambda_1'), \quad (3)$$

where $u(p,\lambda)$'s are LF bi-spinors of proton and neutron[17] and $\epsilon_{i,j}$ is two dimensional Levi-Civita tensor, with $i,j = \pm 1$ helicity of nucleon. Since the deuteron is a pseudo-vector "particle", due to γ_5 in Eq.(3), the vertex Γ_d^μ is a four-vector which we can construct in a general form that explicitly satisfies time reversal, parity and charge conjugate symmetries. Noticing that at the $d \to pn$ vertex on the light-front the "-" ($p_- = E - p_z$) components of the four-momenta of the particles are not conserved, in addition to the four-momenta of two nucleons, p_1^μ and p_2^ν one has additional four-momentum:

$$\Delta^\mu \equiv p_1^\mu + p_2^\mu - p_d^\mu \equiv (\Delta^-, \Delta^+, \Delta_\perp) = (\Delta^-, 0, 0), \quad (4)$$

where

$$\Delta^- = p_1^- + p_2^- - p_d^- = \frac{m_N^2 + k_\perp^2}{p_1^+} + \frac{m_N^2 + k_\perp^2}{p_2^+} - \frac{M_d^2}{p_d^+}$$
$$= \frac{1}{p_d^+}\left[\frac{4(m_N^2 + k_\perp^2)}{\alpha_1(2-\alpha_1)} - M_d^2\right] = \frac{4}{p_d^+}\left[m_N^2 - \frac{M_d^2}{4} + k^2\right]. (5)$$

Here k is the relative momentum in the pn CM system defined as:

$$k = \sqrt{\frac{m_N^2 + k_\perp^2}{\alpha_1(2-\alpha_1)} - m_N^2} \quad \text{and} \quad \alpha_1 = \frac{E_k + k_z}{E_k}, \quad (6)$$

where $E_k = m^2 + k^2$. With p_1^μ, p_2^μ and Δ^μ 4-vectors the Γ_d^μ 4-vector function is constructed in the following form:

$$\Gamma_d^\mu = \Gamma_1\gamma^\mu + \Gamma_2\frac{(p_1-p_2)^\mu}{2m_N} + \Gamma_3\frac{\Delta^\mu}{2m_N} + \Gamma_4\frac{(p_1-p_2)^\mu\not{\Delta}}{4m_N^2}$$
$$+ i\Gamma_5\frac{1}{4m_N^3}\gamma_5\epsilon^{\mu\nu\rho\gamma}(p_d)_\nu(p_1-p_2)_\rho(\Delta)_\gamma + \Gamma_6\frac{\Delta^\mu\not{\Delta}}{4m_N^2}, \quad (7)$$

where Γ_i, $(i = 1,6)$ are scalar functions describing dynamics of pn component being observed in the deuteron.

High Energy Approximation: For large Q^2 limit, LF momenta for reaction (1) are chosen as follows:

$$p_d^\mu \equiv (p_d^-, p_d^+, p_{d\perp}) = \left(\frac{Q^2}{x\sqrt{s}}\left[1 + \frac{x}{\tau} - \sqrt{1+\frac{x^2}{\tau}}\right], \frac{Q^2}{x\sqrt{s}}\left[1 + \frac{x}{\tau} + \sqrt{1+\frac{x^2}{\tau}}\right], 0_\perp\right)$$
$$q^\mu \equiv (q^-, q^+, q_\perp) = \left(\frac{Q^2}{x\sqrt{s}}\left[1 - x + \sqrt{1+\frac{x^2}{\tau}}\right], \frac{Q^2}{x\sqrt{s}}\left[1 - x - \sqrt{1+\frac{x^2}{\tau}}\right], 0_\perp\right), \quad (8)$$

where $s = (q + p_d)^2$, $\tau = \frac{Q^2}{M_d^2}$ and $x = \frac{Q^2}{M_d q_0}$, with q_0 being virtual photon energy in the deuteron rest frame. The high energy nature of this process results in, $p_d^+ \sim \sqrt{Q^2} \gg m_N$. Then one observes in Eq.(5) that the Δ^- term is suppressed by the large p_d^+ factor.

Analyzing now the vertex function (7) one observes that $\frac{\Delta^-}{2m_N}$ enters as a small parameter in the problem in which Γ_3 and Γ_4 terms enter with the order of $\mathcal{O}^1(\frac{\Delta^-}{2m_N})$ while Γ_6 term enters as $\mathcal{O}^2(\frac{\Delta^-}{2m_N})$. Situation with Γ_5 term, is however different; since for the covariant components: $\Delta_+ = \frac{1}{2}\Delta^-$, $p_{d,-} = \frac{1}{2}p_d^+$, the term with $\epsilon^{\mu+\perp-}$ is a leading order ($\mathcal{O}^0(\frac{\Delta^-}{2m_N})$) due to the fact that large p_d^+ factor is cancelled in $p_{d,-}\Delta_+ = \frac{1}{4}p_d^+\Delta^-$ combination.

Keeping the leading, $\mathcal{O}^0(\Delta^-)$, terms in Eq.(7) the LF deuteron wave function reduces to[15, 16]:

$$\psi_d^{\lambda_d}(\alpha_i, p_\perp) = -\sum_{\lambda_2,\lambda_1,\lambda_1'}\bar{u}(p_2,\lambda_2)\left\{\Gamma_1\gamma^\mu + \Gamma_2\frac{(p_1-p_2)^\mu}{2m_N}\right.$$
$$\left. + \sum_{i=1}^{2} i\Gamma_5\frac{1}{8m_N^3}\epsilon^{\mu+i-}p_d^+k_i\Delta^-\right\}\gamma_5\frac{\epsilon_{\lambda_1,\lambda_i'}}{\sqrt{2}}u(p_1,\lambda_1')\chi_\mu^{\lambda_d}, (9)$$

where $k_i = \frac{(p_{1,i}-p_{2,i})}{2}$, for $i = 1,2$. The deuteron's polarization four-vector is chosen as:

$$\chi_\mu^{\lambda_d} = (\chi_0^{\lambda_d}, \chi_\perp^{\lambda_d}, \chi_z^{\lambda_d}) = (\frac{p_{12}s_{d,z}}{M_{12}}, s_{s,\perp}, \frac{E_{12}s_{d,z}}{M_{12}}), \quad (10)$$

where $\mathbf{p_{12}} = (p_{1_z} + p_{2,z}, 0_\perp)$, $E_{12} = \sqrt{M_{12}^2 + p_{12}^2}$ and $M_{12}^2 = s_{NN} = 4\frac{(m_N^2+k_\perp^2)}{\alpha_1(2-\alpha_1)}$.

Since the wave function in Eq.(9) is Lorentz boost invariant along the z axis, it is convenient to calculate it in the deuteron CM frame obtained by boosting with velocity $v = \frac{\mathbf{p_{12}}}{E_{12}}$. Such a transformation results in[16]:

$$\psi_d^{\lambda_d}(\alpha_i, k_\perp) = - \sum_{\lambda_2,\lambda_1,\lambda_1'} \bar{u}(-k,\lambda_2) \Bigg\{ \Gamma_1 \gamma^\mu + \Gamma_2 \frac{\tilde{k}^\mu}{m_N} + \sum_{i=1}^{2} i\Gamma_5 \frac{1}{8m_N^3} \epsilon^{\mu+i-} p_d'^{+} k_i \Delta'^{-} \Bigg\} \gamma_5 \frac{\epsilon_{\lambda_1,\lambda_i'}}{\sqrt{2}} u(k,\lambda_1') s_\mu^{\lambda_d}, \quad (11)$$

where $\tilde{k}^\mu(0,k_z,k_\perp)$ with $k_\perp = p_{1\perp}$, $k^2 = k_z^2 + k_\perp^2$ and $E_k = \frac{\sqrt{s_{NN}}}{2}$ and $s_\mu^{\lambda_d} = (0, \mathbf{s_d^\lambda})$ in which:

$$s_d^1 = -\frac{1}{\sqrt{2}}(1,i,0), \;\; s_d^1 = \frac{1}{\sqrt{2}}(1,-i,0) \;\; s_d^0 = (0,0,1). \quad (12)$$

In Eq.(11) "primed" variables correspond to the Lorentz boosts of respective unprimed quantities:

$$p_d'^{+} = \sqrt{s_{NN}}, \;\; \Delta'^{-} = \frac{1}{\sqrt{s_{NN}}} \left[\frac{4(m_N^2 + k_\perp^2)}{\alpha_1(2-\alpha_1)} - M_d^2 \right]. \quad (13)$$

Since the term related to the Γ_5 is proportional to $\frac{4(m_N^2+k_\perp^2)}{\alpha_1(2-\alpha_1)} - M_d^2$ which diminishes at small momenta, only the Γ_1 and Γ_2 terms will contribute in nonrelativistic limit defining the S- and D- components of the deuteron. Thus LF wave function in Eq.(11) provides a smooth transition to the non-relativistic deuteron wave function. This can be seen by expressing Eq.(11) through two-component spinors:

$$\psi_d^{\lambda_d}(\alpha_1, k_t, \lambda_1, \lambda_2) = \sum_{\lambda_1'} \phi_{\lambda_2}^\dagger \sqrt{E_k} \Bigg[\frac{U(k)}{\sqrt{4\pi}} \sigma \mathbf{s_d^{\lambda_d}} - \frac{W(k)}{\sqrt{4\pi}\sqrt{2}} \left(\frac{3(\sigma\mathbf{k})(\mathbf{k}\mathbf{s_d^\lambda})}{k^2} - \sigma \mathbf{s_d^\lambda} \right) + (-1)^{\frac{1+\lambda_d}{2}} P(k) Y_1^{\lambda_d}(\theta,\phi) \delta^{1,|\lambda_d|} \Bigg] \frac{\epsilon_{\lambda_1,\lambda_1'}}{\sqrt{2}} \phi_{\lambda_1'}. \quad (14)$$

Here the first two terms have explicit S- and D- structures were radial functions defined as:

$$U(k) = \frac{2\sqrt{4\pi}\sqrt{E_k}}{3} \left[\Gamma_1 (2 + \frac{m_N}{E_k}) + \Gamma_2 \frac{k^2}{m_N E_k} \right]$$
$$W(k) = \frac{2\sqrt{4\pi}\sqrt{2E_k}}{3} \left[\Gamma_1 (1 - \frac{m_N}{E_k}) - \Gamma_2 \frac{k^2}{m_N E_k} \right]. \quad (15)$$

This relation is known for pn-component deuteron wave function[11, 18], which allows to model LF wave function through known radial S- and D- wave functions estimated at LF relative momentum k defined in Eq.(6).

However in addition to S-, D- terms, our observation is that due to the Γ_5 term, there is an additional leading contribution, which because of the relation $Y_1^{\pm}(\theta,\phi) = \mp i \sqrt{\frac{3}{4\pi}} \sum_{i=1}^{2} \frac{(k \times s_d^{\pm 1})_z}{k}$, has a P-wave like structure, where P- radial function is defined as:

$$P(k) = \sqrt{4\pi} \frac{\Gamma_5(k)\sqrt{E_k}}{\sqrt{3}} \frac{k^3}{m_N^3}. \quad (16)$$

It is worth emphasizing that this term is purely relativistic in origin: as it follows from Eq.(16) it has an extra $\frac{k^2}{m_N^2}$ factor in addition to the $\frac{k^{l=1}}{m_N}$ term characteristic to the radial P-wave. As a result one has a smooth transition to S- and D-states in nonrelativistic limit.

The interesting feature of the above result which we will discuss in the next section, is that the P-wave is "incomplete", that it contributes only for $\lambda_d = \pm 1$ polarizations of the deuteron.

Closing this section we would like to mention that consideration of six invariant vertex functions and contribution of P-radial waves in relativistic description of the deuteron were discussed earlier in the literature, see e.g. Refs.[20, 21]. However, to the best of our knowledge the observation that Γ_5 is a leading term on the light-front (while $\Gamma_{3,4,6}$ terms are suppressed) in high energy limit and it results in a non-complete P-wave contribution are original results of the present work.

Light Front Density Matrix of the Deuteron: Using Eq.(14) one defines unpolarized deuteron light-front density matrix in the form[2, 11]:

$$\rho_d(\alpha, k_\perp) = \frac{n_d(k,k_\perp)}{2-\alpha}, \quad (17)$$

where LF momentum distribution is expressed through the radial wave functions as follows:

$$n_d(k,k_\perp) = \frac{1}{3} \sum_{\lambda_d=-1}^{1} |\, \psi_d^{\lambda_d}(\alpha,k_\perp)\,|^2 = \frac{1}{4\pi} \left(U(k)^2 + W(k)^2 + \frac{k_\perp^2}{k^2} P^2(k) \right). \quad (18)$$

The LF density matrix satisfies baryonic and momentum sum rules as follows:

$$\int \rho_d(\alpha,k_\perp) \frac{d\alpha}{\alpha} = 1 \quad \text{and} \quad \int \alpha \rho_d(\alpha,k_\perp) \frac{d\alpha}{\alpha} = 1. \quad (19)$$

From the above, the normalization condition for the radial wave functions is:

$$\int \left(U(k)^2 + W(k)^2 + \frac{2}{3} P^2(k) \right) k^2 dk = 1. \quad (20)$$

The Γ_5-Term and Non-Nucleonic Component in the Deuteron: The unusual result of Eq.(14) is that the P-wave like term enters only for deuteron polarizations, $\lambda_d = \pm 1$. The later is the reason that momentum distribution in Eq.(18) depends explicitly on the transverse component of the relative momentum on the light front. Such a behavior is impossible for non-relativistic quantum mechanics of the deuteron since in this case the potential of the interaction is real (no inelasticities) and the solution of Lippmann-Schwinger equation for partial S- and D-waves satisfies "angular condition", according to which the momentum distribution in unpolarized deuteron depends on the magnitude of relative momentum only. Our result do not contradict the properties of non-relativistic deuteron wave function since as it was discussed earlier according to Eq.(16) the P-wave is purely relativistic in its nature. On the other hand, in the relativistic domain the definition of the interaction potential is not straightforward to allow to use quantum-mechanical arguments in claiming that momentum distribution in Eq.(18) should satisfy the angular condition (i.e. depends on magnitude of k only).

For the relativistic domain, on the light-front, the analogue of Lippmann-Schwinger equation is the Weinberg type equation[19] using which for NN scattering amplitude, in which only nucleonic degrees are considered, in the CM of the NN system, one obtains[22]:

$$T_{NN}(\alpha_i, k_{i\perp}, \alpha_f, k_{f,\perp}) \equiv T_{NN}(k_{i,z}, k_{i\perp}, k_{f,z}, k_{f,\perp}) = V(k_{i,z}, k_{i\perp}, k_{f,z}, k_{f,\perp}) + \int V(k_{i,z}, k_{i\perp}, k_{m,z}, k_{m,\perp}) \times \times \frac{d^3k_m}{(2\pi)^3\sqrt{m^2+k_m^2}} \frac{T_{NN}(k_{m,z}, k_{m\perp}, k_{f,z}, k_{f,\perp})}{4(k_m^2 - k_f^2)}, \quad (21)$$

where "i", "m" and "f", subscripts correspond to initial, intermediate and final NN states respectively and momenta $k_{i,m,f}$ are defined similar to Eq.(6). The realization of the angular condition for relativistic case will require that light-front potential to satisfy a condition

$$V(k_{i,z}, k_{i\perp}, k_{m,z}, k_{m,\perp}) = V(\vec{k}_i^2, (\vec{k}_m - \vec{k}_i)^2). \quad (22)$$

Such a conditions is obvious for on-shell limit, since the Lorentz invariance of the T_{NN} amplitude requires:

$$T_{NN}^{on\ shell}(k_{i,z}, k_{i\perp}, k_{m,z}, k_{m,\perp}) = T_{NN}^{on\ shell}(\vec{k}_i^2, (\vec{k}_m - \vec{k}_i)^2) \quad (23)$$

and existence of the Born term in Eq.(21) indicates that the potential V satisfies the same condition in the on-shell limit.

For the off-shell potential the angular condition is not obvious. However in Ref.[2, 22, 23] it was shown that requirements of potential V satisfying angular condition in the on-shell limit and that it can be constructed through the series of elastic pn scatterings result in a potential which is analytic function of angular momentum. Then with the minimal assumption that the potential, analytically continued to the complex angular momentum space, does not diverge exponentially, it was shown that V and the T_{NN} functions satisfy angular condition (Eqs.(22,23)) in general. Then, using the same potential to calculate LF deuteron wave function will result in a momentum distribution that will depend on the magnitude of the relative pn momentum only. This observation requires the restriction by the pn component only in the deuteron.

Inclusion of the inelastic transitions will completely change the LF equation for the pn scattering. For example, contribution of N^*N transition to the elastic NN scattering:

$$T_{NN}(k_{i,z}, k_{i\perp}, k_{f,z}, k_{f,\perp}) = \int V_{NN^*}(k_{i,z}, k_{i\perp}, k_{m,z}, k_{m,\perp}) \times \frac{d^3k_m}{(2\pi)^3\sqrt{m^2+k_m^2}} \frac{T_{N^*N}(k_{m,z}, k_{m\perp}, k_{f,z}, k_{f,\perp})}{4(k_m^2 - k_f^2 + m_{N*}^2 - m_N^2)}, \quad (24)$$

will not require the condition of Eq.(22) with the transition potential having also an imaginary component. Eq.(24 can not be described with any combination of elastic NN interaction potentials that satisfies the angular condition. The same will be true also for $\Delta\Delta \to NN$ and $N_c, N_c \to NN$ transitions. This indicates that if the Γ_5 term is not zero then it should originate from non-nucleonic component in the deuteron.

Estimate of the Possible Effects: Our prediction is that the observation of anisotropic LF momentum distribution depending on the center of mass k and $k_\perp$ separately will indicate the presence of non-nucleonic component in the deuteron. Since this effect is due to the P-wave like structure, (originating from Γ_5 term) which has an extra $\frac{k^2}{m_N^2}$ factor (Eq.(15)) compared to S- and D- radial waves, one expects it to become important at $k > m_N$.

To give qualitative estimate of the possible effects we evaluate Γ_5 vertex function assuming two color-octet baryon transition to the pn system ($N_cN_c \to pn$) through one-gluon exchange, parameterizing it in the dipole form $\frac{A}{(1+\frac{k^2}{0.71})^2}$. The parameter A is estimated by assuming 1% contribution to the total normalization from the P wave in Eq.(20). The latter is consistent with the experimental estimation in Ref.[24] of 0.7%. In Fig.1 we consider dependence of the momentum distribution of Eq.(18) as a function of $\cos\theta = \frac{(\alpha-1)E_k}{k}$ for different values of k. Notice that if momentum distribution is generated by pn component only, the angular condition is satisfied, and no dependence should be observed.

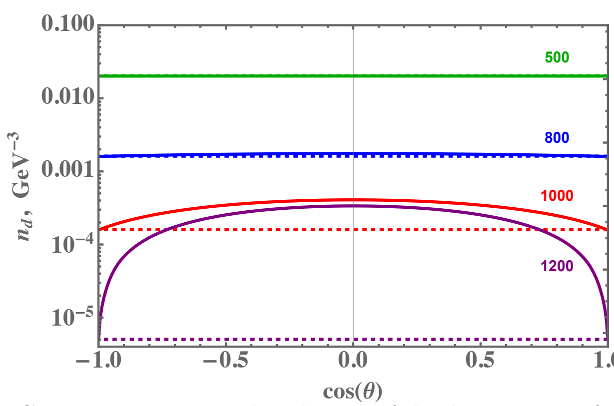

FIG. 1: LF momentum distribution of the deuteron as a function of $\cos\theta$, for different values of k. Dashed lines - deuteron with pn component only, solid lines - with P-wave like component included.

As the figure shows on may expect measurable angular dependence at $k \gtrsim 1$ GeV/C which is consistent with the expectation that inelastic transition in the deuteron corresponding to the non-nucleonic components takes place at $k \gtrsim 800$ MeV/c. Additionally due to the fact that the P-component contributes only for $\lambda_d = \pm 1$ polarization of the deuteron (Eq.(14)) one expects enhanced effect in the asymmetry from scattering off the tensor polarized deuteron:

$$A_T = \frac{n_d^{\lambda_d=1}(k,k_\perp) + n_d^{\lambda_d=-1}(k,k_\perp) - 2n_d^{\lambda_d=0}(k,k_\perp)}{n_d(k,k_\perp)}. \quad (25)$$

As Fig.2 shows the presence of non-nucleonic component will be visible already at $k \approx 800$ MeV/c resulting in a qualitative difference in asymmetry at larger momenta as compared with the asymmetry predicted by deuteron wave function with pn-component only.

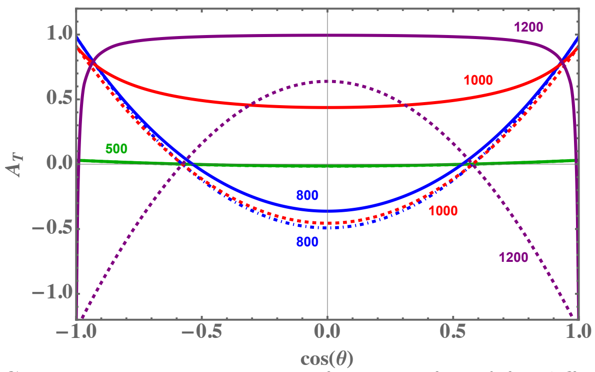

FIG. 2: Tensor asymmetry as a function of $\cos\theta$ for different k. Dashed lines - deuteron with pn component only, solid lines - with P component included.

Outlook on Experimental Verification of the Effect: Prediction that non-nucleonic component in the deuteron wave function may result in angular dependence of LF-momentum distribution can be verified at CM momenta $k \gtrsim 1$ GeV/c. This seems incredibly large momenta to be measured in experiment. However the first such measurement at high Q^2 disintegration of the deuteron is already performed at Jefferson Lab[25] reaching $k \sim 1$ GeV/c. It is intriguing that the results of this measurement qualitatively disagree with predictions based on conventional deuteron wave function once $k \gtrsim 800$ MeV/C. The planned new measurement[26] will significantly improve the quality of the data allowing possible verification of the effects discussed in this work. It is worth mentioning that the analysis of the experiment will require careful account for competing nuclear effects such as final state interaction for which there is a significant theoretical and experimental progress during the last decade[27, 28]. If the experiment will not find the angular dependence in the momentum distribution this will allow to set a new limit on the dominance of pn component at instantaneous high nuclear densities that corresponds to ~ 1 GeV/c internal momentum in the deuteron. If, however, the angular dependence is found, it will motivate theoretical modeling of non-nucleonic components in the deuteron, such as $\Delta\Delta$, N^*N or hidden-color N_cN_c that can reproduce the observed result. In both cases results of such studies will advance the understanding of the dynamics of high density nuclear matter and the relevance of the quark-hadron transition. Possibility of studies of tensor asymmetries will significantly complement above studies, however feasibility of such experiments currently is not clear.

Acknowledgments: We are thankful to Drs. Leonid Frankfurt and Mark Strikman for useful discussions. This work is supported by the U.S. DOE Office of Nuclear Physics grant DE-FG02-01ER41172.

[1] J. J. Aubert *et al.* [European Muon], Phys. Lett. B **123**, 275-278 (1983).
[2] L. L. Frankfurt and M. I. Strikman, Phys. Rept. **160**, 235-427 (1988).
[3] O. Hen, G. A. Miller, E. Piasetzky and L. B. Weinstein, Rev. Mod. Phys. **89**, no.4, 045002 (2017).
[4] J. Seely, *et al.* Phys. Rev. Lett. **103**, 202301 (2009).
[5] L. B. Weinstein, *et al.* Phys. Rev. Lett. **106**, 052301 (2011).
[6] B. Schmookler *et al.* [CLAS], Nature **566**, no.7744, 354-358 (2019).
[7] E. Fonseca, *et al.* Astrophys. J. Lett. **915**, no.1, L12 (2021).
[8] M. C. Miller, *et al.* Astrophys. J. Lett. **918**, no.2, L28 (2021).
[9] W. Melnitchouk, M. Sargsian and M. I. Strikman, Z. Phys. A **359**, 99-109 (1997).
[10] R. P. Feynman, "Photon-hadron interactions, "CRC Press (January 1, 1972).
[11] L. Frankfurt and M. Strikman, Phys. Rept. **76**, 215-347 (1981).
[12] G. A. Miller, Prog. Part. Nucl. Phys. **45**, 83-155 (2000).
[13] S. J. Brodsky, H. C. Pauli and S. S. Pinsky, Phys. Rept. **301**, 299-486 (1998).
[14] T. Frederico, E. M. Henley and G. A. Miller, Nucl. Phys. A **533**, 617-641 (1991).
[15] F. Vera, [arXiv:2108.11502 [nucl-th]].
[16] M.M. Sargsian and F. Vera, *in progress*
[17] G. P. Lepage and S. J. Brodsky, Phys. Rev. D **22**, 2157 (1980).
[18] J. Carbonell and V. A. Karmanov, Nucl. Phys. A **581**, 625-653 (1995).
[19] S. Weinberg, Phys. Rev. **150**, 1313-1318 (1966).
[20] W. Buck and F. Gross, Phys. Rev. D **20**, 2361 (1979).
[21] J. Carbonell, B. Desplanques, V. A. Karmanov and J. F. Mathiot, Phys. Rept. **300**, 215-347 (1998).
[22] L. L. Frankfurt and M. I. Strikman, in *Modern topics in electron scattering*, edited by B. Frois and I. Sick, 1991.
[23] L.L. Frankfurt, M.I. Strikman, L. Mankiewicz, and M. Sawicki, Few-Body Systems **8**, 37-43 (1990).
[24] P. V. Degtyarenko, Y. V. Efremenko, V. B. Gavrilov and G. A. Leksin, Z. Phys. A **335**, 231-238 (1990).
[25] C. Yero *et al.* [Hall C], Phys. Rev. Lett. **125**, no.26, 262501 (2020).
[26] W. U. Boeglin, *et al.* [arXiv:1410.6770 [nucl-ex]].
[27] M. M. Sargsian, Phys. Rev. C **82**, 014612 (2010).
[28] W. Boeglin and M. Sargsian, Int. J. Mod. Phys. E **24**, no.03, 1530003 (2015).