“High $p_T$ spin physics”

S.S. Shimanskiy (LHEP JINR, Dubna)
“Spin plays a dramatic Jekyll and Hyde role in the theatre of elementary article physics, acting sometimes as the harbinger of the demise of a current theory, sometimes as a powerful tool in the confirmation and verification of such a theory.”
Outline

1. The problems in high $p_T$ region
2. Deuteron
3. What will do at NICA@Nuclotron
SUMMARY
For the past 30 years QCD-based calculations have continued to disagree with the ZGS 2-spin & AGS 1-spin elastic data and the ZGS, AGS, Fermilab & RHIC inclusive data.
* These large spin effects do not go to zero at high-energy or high-$P_{\perp}$ as was predicted.
* No QCD-based model can explain all the large spin effects.

BASIC PRINCIPLE OF SCIENCE:
If a theory does not agree with reproducible experimental data, then the theory must be modified.
These precise spin experiments provide experimental guidance for the required modification of the theory of Strong Interactions.
Elastic $d\sigma/dt$, $A_{nn}$ and $A_n$ experiments at higher energy and $P_{\perp}$ could provide more guidance, just as the RHIC inclusive $A_n$ experiments confirmed the similar Fermilab experiments. (E-704 Yokosawa et al.).
2-SPIN PROTON-PROTON ELASTIC CROSS SECTIONS

12 GeV ZGS
1977-1978

SPINS PARALLEL 4X SPINS ANTIPARALLEL
TOTALLY UNEXPECTED

Questions by Profs. Weisskopf & Bethe:
High $P_T$ or $90^\circ_{cm}$ Identical Particles?
Answer to Questions by Profs. Weisskopf & Bethe

$p+p \rightarrow p+p$

- **90°**
- **11.75 GeV/c**

ZGS 1979

ZGS 1978
Fig. 16. Test of fixed $\theta_{CM}$ scaling for elastic pp scattering. The best fit gives the power $N = 9.7 \pm 0.5$ compared to the dimensional counting prediction $N=10$. Small deviations are not readily apparent on this log-log plot. The compilation is from Landshoff and Polkinghorne.
AGS 1985-1990 $A_n$
PERTURBATIVE QCD $\Rightarrow$
$A_n = 0$ at HIGH $P_{\perp}^2$ and HIGH ENERGY

$A_n \neq 0 \Rightarrow$
PROBLEM with PQCD?

NO MODEL can EXPLAIN ALL
HIGH-$P_{\perp}^2$ SPIN EFFECTS ($A_n$ & $A_{nn}$)

GOAL
MEASURE $A_n$ (and $A_{nn}$)
up to $P_{\perp}^2 = 12$ (GeV/c)
INCLUSIVE HYPERON POLARIZATION
Devlin, Pondrum, Bunce, Heller et al. 1976-80
Fermilab 400 GeV p+p → Lambda ----
Plot by Heller ~1980
with KEK & ISR data

P ~ 15-20 %
QCD says P ~ 0
INCLUSIVE PION PRODUCTION

200 GeV Polarized Proton Beam
from Polarized Hyperon Decay

1990s  Fermilab E-704
Yokosawa et al.


\[ A_n \sim 40\% \]

QCD said \( A_n \sim 0 \)
INCLUSIVE PION ASYMMETRY IN PROTON-PROTON COLLISIONS
C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009

ZGS 12 GeV

AGS 22 GeV

FNAL 200 GeV

RHIC $s = 3900$ GeV$^2$

$A_N(\%)$

$X_F$

PRL 36, 929 (1976)

PRD 65, 092008 (2002)

PLB 261, 201 (1991)

PLB 264, 462 (1991)

BRAHMS

PRL 101, 042001 (2008)
There are no spin data for other NN systems (nn and np)!!!
Deuteron Spin Structure
DEUTERON STATIC PROPERTIES FROM NN-POTENTIALS

Table 1: Deuteron properties in the dressed bag model.

<table>
<thead>
<tr>
<th>Model</th>
<th>$E_d$(MeV)</th>
<th>$P_D$(%)</th>
<th>$r_m$(fm)</th>
<th>$Q_d$(fm$^2$)</th>
<th>$\mu_d/\mu_N$</th>
<th>$A_S$(fm$^{-1/2}$)</th>
<th>$\eta(D/S)$</th>
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<tr>
<td>RSC</td>
<td>2.22461</td>
<td>6.47</td>
<td>1.957</td>
<td>0.2796</td>
<td>0.8429</td>
<td>0.8776</td>
<td>0.0262</td>
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<tr>
<td>Moscow 99</td>
<td>2.22452</td>
<td>5.52</td>
<td>1.966</td>
<td>0.2722</td>
<td>0.8483</td>
<td>0.8844</td>
<td>0.0255</td>
</tr>
<tr>
<td>Bonn 2001</td>
<td>2.224575</td>
<td>4.85</td>
<td>1.966</td>
<td>0.270</td>
<td>0.8521</td>
<td>0.8846</td>
<td>0.0256</td>
</tr>
<tr>
<td>DBM (1)</td>
<td>2.22454</td>
<td>5.22</td>
<td>1.9715</td>
<td>0.2754</td>
<td>0.8548</td>
<td>0.8864</td>
<td>0.0259</td>
</tr>
<tr>
<td>$P_{in} = 3.66%$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>DBM (2)</td>
<td>2.22459</td>
<td>5.31</td>
<td>1.970</td>
<td>0.2768</td>
<td>0.8538</td>
<td>0.8866</td>
<td>0.0263</td>
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<tr>
<td>$P_{in} = 2.5%$</td>
<td></td>
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</tr>
<tr>
<td>experiment</td>
<td>2.224575</td>
<td></td>
<td>1.971</td>
<td>0.2859</td>
<td>0.8574</td>
<td>0.8846</td>
<td>0.0263</td>
</tr>
</tbody>
</table>

Problem to built SPIN from the constituents - for deuteron too!
CURRENT EXPERIMENTS USING POLARIZED BEAMS OF THE JINR VBLHE ACCELERATOR COMPLEX

F. Lehar

DAPNIA, CEA/Saclay, Gif-sur-Yvette Cedex, France
Fig. 16. The summary of the data for backward elastic scattering $p(d, p)d$. The EMD is extracted from the data presented in Fig. 15. Line — One-Nucleon-Exchange (ONE) predictions with Paris DWF. The upper scale illustrates the correspondence between $T_p$ and $k$. 
Fig. 13. World data for deuteron break-up on protons and carbon nuclei. The Empirical Momentum Density (EMD), denoted here as $\Phi^2$, is defined in the text. Lines are calculated in the quasi-impulse approximation with different models for the deuteron wave function (DWF) (labels «Paris», «Nij93», «NijI» for the Paris and Nijmegen DWFs) and in the model where rescattering effects and final state interactions are taken into account («Lyka92»[103, 104]).

a) $\bigcirc$ — $H(d, p)X$ (Dubna); $\blacktriangle$ — $d(e', e')X$ (SLAC); $\blacklozenge$ — $C(d, p)X$ (Dubna, 1988); $\bigcirc$ — $p(d, p)X$ (Dubna, 1994); $\blacksquare$ — $C(d, p)X$ (Dubna, 1995);
b) $\bullet$ — Saclay (1991); $\blacksquare$ — ALPHA (1992); $\bigstar$ — ANOMALON (1993); $\triangle$ — ALPHA (1994)
2.3 Where is confinement?

The quark–gluon picture works rather well across the board. Moreover, in many cases it seems to work *too well*. This is another worry: too good to be true ain’t good enough.

Too early?

The way the differential large angle $2 \to 2$ particle scattering cross sections should scale with energy (momentum transfer) was envisaged by the so-called “quark counting rules” [26],

$$\frac{d\sigma}{dt} = \frac{f(\Theta)}{s^{K-2}}, \quad \frac{t}{s} = \text{const},$$

with $K$ the number of elementary fields (quarks, photons, leptons, etc.) among / inside the initial and final particles.

For example, in the case of the deuteron break-up by a photon, $\gamma + D \to p + n$, we have $K = 1 + 6 + 6 = 13$ (a photon and 6 quarks inside the initial deuteron and another 6 in the final proton and neutron). So, the differential cross section is expected to fall with $s$, asymptotically, as $s^{-31} = E_{CM}^{-22}$.

The key word *asymptotically* always provided an excuse for unversed HEP theorists in their encounters with angered experimenters. The JLAB plot in Fig. 1 which I borrowed from Paul Hoyer’s talk [27] seems to be telling us that this standard excuse is unnecessary here. However, it is again unnerving but for precisely opposite reason, if you take my meaning. Indeed, it is *very difficult* to digest how the naive asymptotic regime manage to settle that early! The lab. energy $1 \text{ GeV}$ of the incident photon, where the scaling behaviour starts, is just too low.

The “counting rules” invite us to view a fast deuteron as a system of six comoving valence quarks. One of them is punched by the photon. The other five we have to properly push ourselves so as to make them fit into two outgoing nucleons. This is done by exchanging five gluons between the quarks in the *scattering amplitude* so that the *cross section* acquires the factor $\alpha_s^{10}$. The picture makes sense as long as 1) the deuteron is indeed fast and 2) typical momentum transfers $q^2$ between quarks are large enough to allow us to use the concept of gluon exchange and of the QCD coupling ($\alpha_s(q^2)$) for that matters. None of these conditions holds for $E_\gamma \approx 1 \text{ GeV}$.

Nonetheless we would have had every right to feel happy about Fig. 1 provided we could convincingly answer but one question: why is such precocious scaling not seen for simpler systems and in particular for the simplest of them all – the electromagnetic form factor of a pion?
Figure 8: Fits of the cross sections $d\sigma/dt$ to $s^{-11}$ for $P_T \geq P_T^{th}$ and proton angles between $30^\circ$ and $150^\circ$ (solid lines). Data are from CLAS (full/red circles), Mainz(open/black squares), SLAC (full-down/green triangles), JLab Hall A (full/blue squares) and Hall C (full-up/black triangles). Also shown in each panel is the $\chi^2$ value of the fit. From Ref. [160].
Measurement of the cross-section asymmetry of deuteron photodisintegration process by linearly polarized photons in the energy range $E_\gamma = 0.8$–$1.6$ GeV

$$\Sigma = (N_n \rightarrow -N_n \uparrow)/(\bar{P}_\gamma \uparrow N_n \rightarrow +\bar{P}_\gamma \rightarrow N_n \uparrow)$$

**Fig. 8.** The energy dependence of the cross-section asymmetry $\Sigma$ for $\theta_p = 90^\circ$ in the cms.
NICA@Nuclotron
Outlook: Status of the NICA construction

- Preparations to tender, Russian state expertise;
- Goal for 2013: to start NICA collider infrastructure realization work
NICA Layout in Polarized Mode
Polarization control scheme in the Collider with spin tune $\nu = 0$

If the two identical Siberian Snakes will be inserted in the opposite straight sections of the collider, then the spin tunes is equal to zero for any energies.

Blue arrows correspond to the case of longitudinal polarization in SPD, whereas the red ones – to vertical polarization in SPD.

Any arbitrary polarization direction of the particle is repeated after each turn. Thus, the possibility to stabilize any direction of the polarization at any point of the particle orbit by means of a small longitudinal field for different particle species is occurred.
Conclusions for NICA-Spin mode

- The novel scheme of spin direction control in NICA collider suitable for any type of the particles is proposed.
- The scheme, designed for protons need lower longitudinal field integral than at the single-snake one. Deuteron polarization control looks much more feasible.
- The scheme provides the desired polarization direction in the both IP’s (MPD and SPD detectors), and gives also a possibility of simple decision the problems of polarization matching at injection and polarimetry.
- Realization of both as single - and multi - turn Spin Flipping systems are possible in such system.
NICA Collision place for SPIN physics
(deuteron and other beams, the first time all isotope states for NN system: \( pp, pn, nn \).)
N↑N↑ studies at $x_T \sim 1$

$N \uparrow + N \uparrow \rightarrow BB + MM$

$B (p, n, \Lambda, \Delta ...), M (\pi, K, ...)$

$N \uparrow N \uparrow \rightarrow NN$

The counting rules and isotopic symmetry studies, $p_T \sim 2$ GeV/c anomaly

$N \uparrow N \uparrow \rightarrow BB + \pi\pi(KK)$

$N \uparrow N \uparrow \rightarrow \Delta\Delta$

Detail vertexes studies:

$q + (q) - (\text{quark} - \text{quark})$

$q + (qq) - (\text{quark} - \text{diquark})$

$(qq) + (qq) - (\text{diquark} - \text{diquark})$
High $p_T$ exclusive reactions $\rightarrow$ MPI

\[ p \uparrow + p \uparrow \rightarrow B + B + M\overline{M} \]
\[ p \uparrow + p \uparrow \rightarrow p + p + \pi^0 \pi^0 (\pi^+ \pi^-) \]

\[ R = \frac{N(\pi^+ \pi^-)}{N(\pi^0 \pi^0)} = \frac{2}{7} \]
\[ R = \frac{N(\pi^0 \pi^0)}{N(\pi^0 \pi^0)} \rightarrow 0 \]

Diquark (S=0)
The End
In 1973 were published two articles:


Predictions that for momentum $p_{\text{beam}} \geq 5$ GeV/c in any binary large-angle scattering ($\theta_{\text{cm}} > 40^\circ$) reaction at large momentum transfers $Q = \sqrt{-t}$:

$$A + B \rightarrow C + D$$

$$\frac{d\sigma}{dt}_{A+B\rightarrow C+D} \sim S^{-(n_A+n_B+n_C+n_D-2)} f\left(\frac{t}{S}\right)$$

where $n_A, n_B, n_C$ and $n_D$ the amounts of elementary constituents in $A, B, C$ and $D$.

$$s = (p_A + p_B)^2 \quad \text{and} \quad t = (p_A - p_C)^2,$$

$$\frac{d\sigma}{dt}_{pp\rightarrow pp} \sim S^{-10} \quad \text{and} \quad \frac{d\sigma}{dt}_{\pi p\rightarrow \pi p} \sim S^{-8}.$$
Indication of asymptotic scaling in the reactions $dd \rightarrow p^3\text{H}$, $dd \rightarrow n^3\text{He}$ and $pd \rightarrow pd$

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Resubmitted 28 February 2005

It is shown that the differential cross sections of the reactions $dd \rightarrow n^3\text{He}$ and $dd \rightarrow p^3\text{H}$ measured at c.m.s. scattering angle $\theta_{cm} = 60^\circ$ in the interval of the deuteron beam energy 0.5–1.2 GeV demonstrate the scaling behaviour, $d\sigma/dt \sim s^{-22}$, which follows from constituent quark counting rules. It is found also that the differential cross section of the elastic $dp \rightarrow dp$ scattering at $\theta_{cm} = 125–135^\circ$ follows the scaling regime $\sim s^{-16}$ at beam energies 0.5–5 GeV. These data are parameterized here using the Reggeon exchange.

Fig. 2. The differential cross section of the $dd \rightarrow n^3\text{He}$ and $dd \rightarrow p^3\text{H}$ reactions at $\theta_{cm} = 60^\circ$ (a), (b) and $dp \rightarrow dp$ at $\theta_{cm} = 125^\circ$ (c), (d) versus the deuteron beam kinetic energy. Experimental data in (a), (b) are taken from [20]. In (c), (d), the experimental data (black squares), (o), (Δ), (open square) and (●) are taken from [22–26], respectively. The dashed curves give the $s^{-22}$ (a) and $s^{-16}$ (c) behaviour. The full curves show the result of calculations using Regge formalism given by Eqs. (2), (3), (4) with the following parameters: (b) $C_1 = 1.9\text{ GeV}^2$, $R_1^2 = 0.2\text{ GeV}^{-2}$, $C_2 = 3.5$, $R_2^2 = -0.1\text{ GeV}^{-2}$; (d) $C_1 = 7.2\text{ GeV}^2$, $R_1^2 = 0.5\text{ GeV}^{-2}$, $C_2 = 1.8$, $R_2^2 = -0.1\text{ GeV}^{-2}$. The upper scales in (a) and (c) show the relative momentum $q_{pn}$ (GeV/c) in the deuteron for the ONE mechanism.
Spin of Proton from Polarized DIS

\[ \frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle \]

- Quark and anti-quark polarization

\[ \langle S_q \rangle = \frac{1}{2} \int_0^1 \Delta \Sigma(x, Q^2) \, dx \approx 0.1 \]

\[ \Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \]

- Gluon contribution

\[ \langle S_g \rangle(Q^2) = \int_0^1 \Delta g(x, Q^2) \, dx \]
mission: exploring the 3-dimensional phase-space structure of the nucleon

intrinsic motion
spin-$k_{\perp}$ correlations?
orbiting quarks?

Ideally: obtain a quantum phase-space distribution (like the Wigner function)
in 1-dimensional QM:

$$\int dp \, W(x, p) = |\psi(x)|^2$$
$$\int dx \, W(x, p) = |\phi(p)|^2$$
$$\langle \hat{O}(x, p) \rangle = \int dx \, dp \, W(x, p) \, O(x, p)$$
New possibilities with $k_T$ account.

(T-odd **Boer-Mulders** and **Sivers** were “forbidden” by T-parity and hermiticity but reanimated by Brodsky and Collins.)
$^{12}\text{C} - \text{structure}$

RNP - program at JINR

V.V.B., V.K.Lukyanov, A.I.Titov, PLB, 67, 46(1977)

$^{12}\text{C} - \text{structure}$

eA - program at JLab

\[ p_T \sim 2 \text{ GeV/c region} \]

**Fig. 20.** Comparison of the cross-section ratio \( p/\pi^+ \) measured on tungsten at \( \sqrt{s} = 23.7 \text{ GeV} \) (closed circles), with that obtained by extrapolation to \( A=1 \) (open circles). Ratios obtained from the British-Scandinavian collaboration (Ref. 23) at \( \sqrt{s} = 23.4 \text{ GeV} \) are also plotted (closed squares).

Fig. 3. [10] Ratio of the cross sections for the production of protons and charged pions as a function of the transverse momentum for various degrees of centrality and two beam energies of 62.4 and 200 GeV: (points) results of the STAR experiment and (curves) results of model calculations.
- С ростом поперечного импульса наблюдается значительно больший выход протонов по отношению к пионам.

- Отсутствие зависимости $p/t$ от атомного числа может рассматриваться как указанием на локальный механизм образования частиц и малый вклад процессов вторичного взаимодействия.

FODS: B. Абрамов и др., ЯФ, т.41, вып.2, 357-370 (1985)

2-х партонный + 3-х партонный + …
TABLE V. The scaling between E755 and E838 has been measured for eight meson-baryon and 2 baryon-baryon interactions at $\theta_{\text{c.m.}} = 90^\circ$. The nominal beam momentum was 5.9 GeV/c and 9.9 GeV/c for E838 and E755, respectively. There is also an overall systematic error of $\Delta n_{\text{syst}} = \pm 0.3$ from systematic errors of $\pm 13\%$ for E838 and $\pm 9\%$ for E755.

<table>
<thead>
<tr>
<th>No.</th>
<th>Interaction</th>
<th>E838</th>
<th>E755</th>
<th>$^{\frac{d\sigma}{dt}} \sim 1/s^{n-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\pi^+ p \rightarrow p\pi^+$</td>
<td>132 ± 10</td>
<td>4.6 ± 0.3</td>
<td>6.7 ± 0.2</td>
</tr>
<tr>
<td>2</td>
<td>$\pi^- p \rightarrow p\pi^-$</td>
<td>73 ± 5</td>
<td>1.7 ± 0.2</td>
<td>7.5 ± 0.3</td>
</tr>
<tr>
<td>3</td>
<td>$K^+ p \rightarrow pK^+$</td>
<td>219 ± 30</td>
<td>3.4 ± 1.4</td>
<td>8.3$^{+0.6}_{-1.0}$</td>
</tr>
<tr>
<td>4</td>
<td>$K^- p \rightarrow pK^-$</td>
<td>18 ± 6</td>
<td>0.9 ± 0.9</td>
<td>≥ 3.9</td>
</tr>
<tr>
<td>5</td>
<td>$\pi^+ p \rightarrow pp^+$</td>
<td>214 ± 30</td>
<td>3.4 ± 0.7</td>
<td>8.3 ± 0.5</td>
</tr>
<tr>
<td>6</td>
<td>$\pi^- p \rightarrow pp^-$</td>
<td>99 ± 13</td>
<td>1.3 ± 0.6</td>
<td>8.7 ± 1.0</td>
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<tr>
<td>13</td>
<td>$\pi^+ p \rightarrow \pi^+\Delta^+$</td>
<td>45 ± 10</td>
<td>2.0 ± 0.6</td>
<td>6.2 ± 0.8</td>
</tr>
<tr>
<td>15</td>
<td>$\pi^- p \rightarrow \pi^+\Delta^-$</td>
<td>24 ± 5</td>
<td>≤ 0.12</td>
<td>≥ 10.1</td>
</tr>
<tr>
<td>17</td>
<td>$pp \rightarrow pp$</td>
<td>3300 ± 40</td>
<td>48 ± 5</td>
<td>9.1 ± 0.2</td>
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<tr>
<td>18</td>
<td>$\overline{p}p \rightarrow \overline{p}p$</td>
<td>75 ± 8</td>
<td>≤ 2.1</td>
<td>≥ 7.5</td>
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</tbody>
</table>
Уважаемые коллеги,

С недавнего времени многопартонные взаимодействия (MPI) привлекают пристальное внимание как теоретиков, так и экспериментаторов. На сегодняшний день теоретики разработали адекватный инструмент для описания двойных жёстких соударений – обобщённое двухпартонное распределение (generalized double parton distribution) $G$. Адекватные монтекарловские модели для описания MPI находятся в стадии разработки. Используя данные HERA по электророждению векторных мезонов, структуру этого нового объекта можно предсказать в области $0.001 < x < 0.1$. В то же время, в области $x > 0.1$ информация о $G$ практически отсутствует. Пертurbationные эффекты в $G$ (весьма серьёзные при больших поперечных импульсах регистрируемых частиц и/или струй) находятся под контролем. Однако, о непертurbationной корреляции партонов внутри волновой функции адрона информации у нас нет. Без прямой экспериментальной информации прогресс в этой области вряд ли возможен. Важно, что для экспериментального изучения этих корреляций не нужны сверхвысокие энергии. Достаточно правильно заданных вопросов и грамотного поставленного эксперимента. Чрезвычайно важной представляется возможность разделения процессов по флейвору участвующих партонов. Измерять корреляции частиц в конечном состоянии вместо адронных струй представляется мне предпочтительным. Дело в том, что эта наблюдаемая содержит ту же информацию о корреляции начальных партонов, что и измерение струй, однако свобода от неопределённостей, связанных с выбором и использованием алгоритма по определению струй. 

Ю. Докшицер
27.02.2013