Investigation of exclusive reactions with d+d and d+p in the initial state at the NICA SPD facility

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31 August 2020

Content (in a free order)

- Problems to be solved by the project
- Existing explanation of attenuation of the color transparency (CT)
- Possible connection of CT explanation with papers of Troyn and Baldin-Stavinskiy et al.
- A new method for experimental study of CT
- What and how should be measured
- Feasibility and pitfalls
- Measurement of the deuteron wave function

Problem 1:

There are no reliable data on the range of applicability and accuracy of the short-range correlation model

Data of Jlab Hall A collaboration

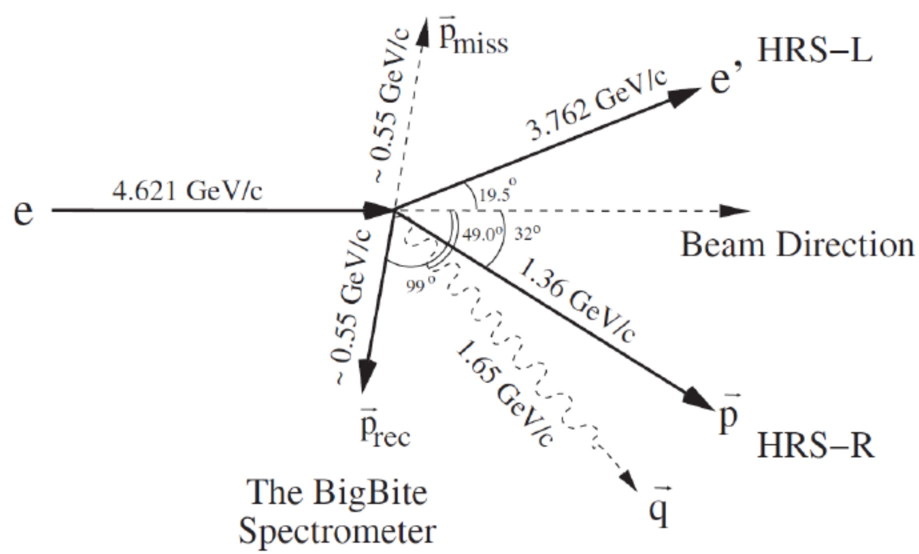


Fig.1,

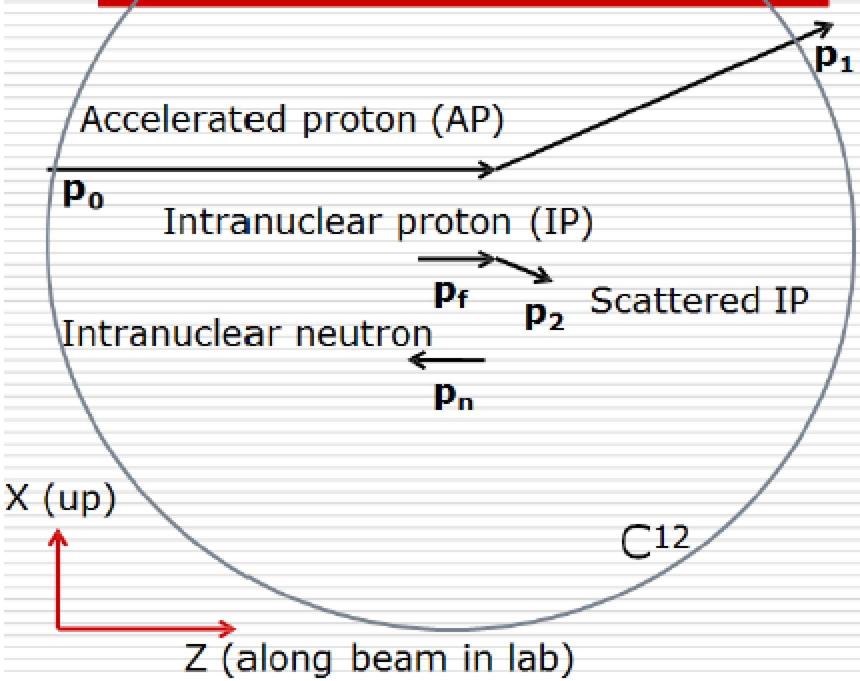
$E_{in} = E_{out} + 294$ *MeV ???*

It is possible to check that with the quasi-free knock-out assumption a situation shown in Fig.1 corresponds to violation of the energy conservation law at a level of 294 MeV.

See ***Phys.Rev. Lett. 99 (2007) 072501***

There are no reliable data on the range of applicability and accuracy of the short-range correlation model

Experiment at BNL with EVA spectrometer



Model of Quasifree Knockout (MQK): IP is knocked out by AP, neutron is a freely outgoing particle.

Experimentally observed mean values and fluctuations of P_z^{cm} and P_z^{rel} can be explained by the Fermi motion in C^{12}.

<u>MQK and SRC agrees with the experiment</u> for P_z^{cm} and P_z^{rel}.

J. Aclander et al Phys. Lett. B 453, 211 (1999)
A. Tang et al Phys. Rev. Lett. 90, 042301 (2003)

There are no reliable data on the range of applicability and accuracy of the short-range correlation model

We **confirm** the results of EVA kinematic analysis for the longitudinal projection of momenta (in z-direction in the picture)
We found a disagreement of the Model of Quasifree Knockout with the experiment for P_x^{cm} and P_x^{rel} (in vertical direction)*).

Compare:

$$\langle P_z^{cm}\rangle \approx 0,\ \sigma_z^{cm} \approx 0.1,\ \langle P_z^{rel}\rangle \approx 0.3,\ \sigma_z^{rel} \approx 0.1,$$

$$\langle P_{x_{cm}}\rangle \approx 0,\ \sigma_{x_{cm}} \approx 0.6,\ \langle P_{x_{rel}}\rangle \approx 0.6,\ \sigma_{x_{rel}} \approx 0.2,$$

The difference between P_x^{rel} and P_z^{rel} can be explained if we take into account a momentum transfer from the struck nucleon to the "spectator".

⇩

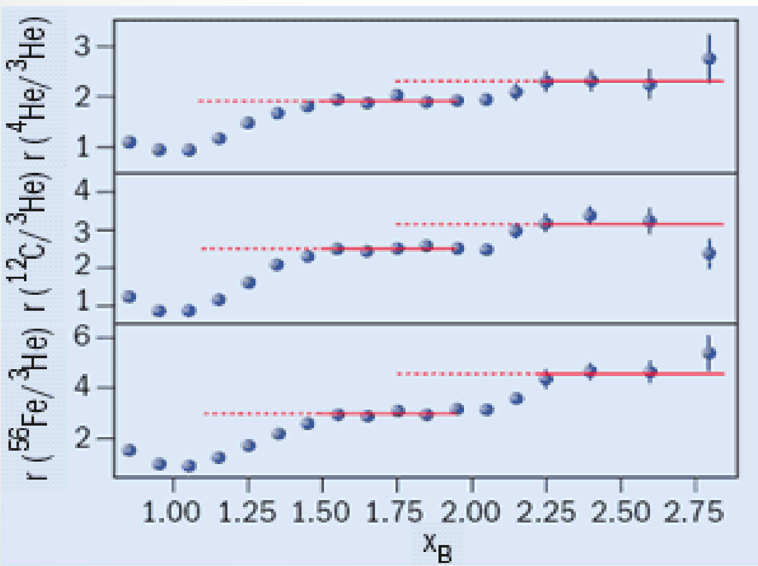
<u>The quasi-free knockout assumption does not work</u>.

*) See details in B.F.K. arXiv:1902.05252v5[nucl-th]

Few-nucleon correlations or multiquark clusters?

Mark Strikman

CERN COURIER, 2 November 2005



Cross-section ratios of ^{4}He, ^{12}C and ^{56}Fe to ^{3}He, normalized to mass A, as a function of x for $Q^2 > 1.4$ GeV^2.

Close nucleon (?) encounters

K. Rith, Nucl. Phys A 532 (1991) 3c

In the region $x > 1$ the struck quark is 'superfast', its momentum is larger than the momentum allowed for a stationary nucleon. The longitudinal distances involved are $z < 0.2$ fm and therefore one is sensitive to correlations of nearby nucleons or more complicated configurations like multiquark clusters. As an example the predictions for a multiquark cluster calculation [32] are shown in figure 5.

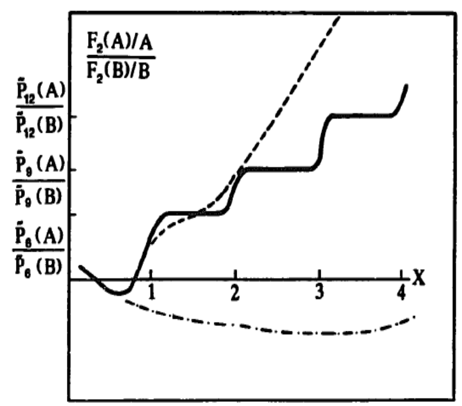


Figure 5. Theoretical predictions for nuclear structure functions at $x > 1$

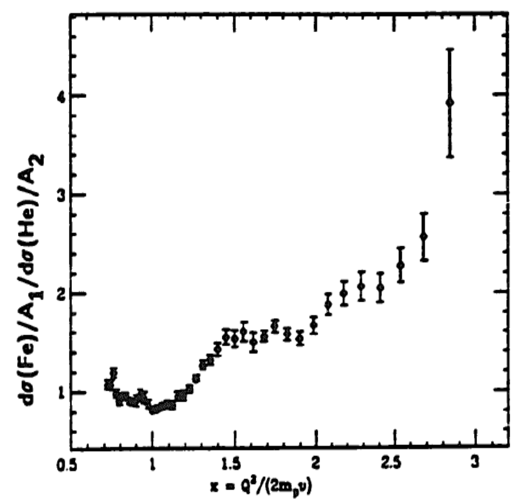


Figure 6. Preliminary results for σ^{Fe}/σ^{He} from NE-2 at SLAC

32 J. Vary, Proceedings of the 7th Int. Conf. on High Energy Physics problems, Dubna 1984,147.

Fluctons or short-range correlations of modified nucleons?

Recent modification of the SRC model:

“nucleons are modified substantially when they fluctuate into SRC pairs”.

Authors of [1] rename the previous version of the SRC correlations into 2N-SRC ones, or **two-nucleon clusters**, and reserve the name SRC correlations for the new hypothetical objects. Logically, it would be better to save the old name for the Frankfurt-Strikman SRC and to give a new denomination to the new objects. Since the suggested fluctuations of the nuclear density are supposed to have **modified quark momentum distribution which is the characteristic property of the fluctons** *(A.V. Efremov, V. V. Burov, V. K. Lukyanov, A. I. Titov)*, that makes sense to designate them as the **flucton phase** of the SRC pairs.

[1] O. Hen, G.A. Miller, E. Piasetzky, L.B. Weinstein, Rev. Mod. Phys. 89 (2017) 045002

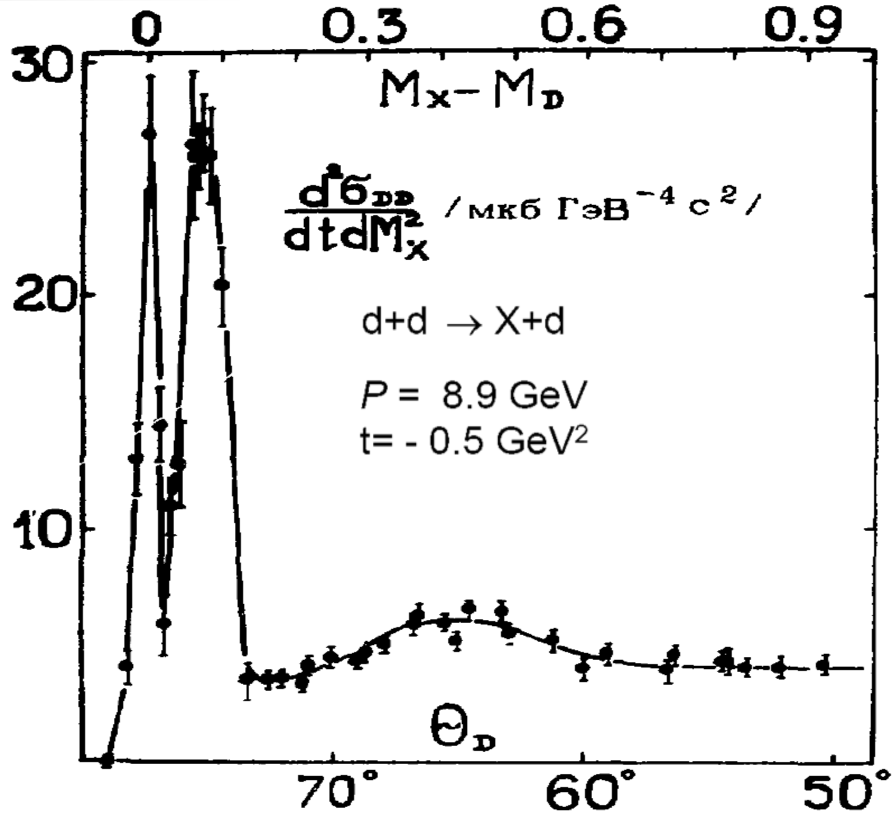
[2] B. Schmookler et al.,(the CLAS Collaboration), Nature 566 (2019) 354

Toward Problem 2:

Data from Baldin-Stavinskiy et al.*)

d+d → X+d

P = 8.9 GeV
t= - 0.5 GeV^2

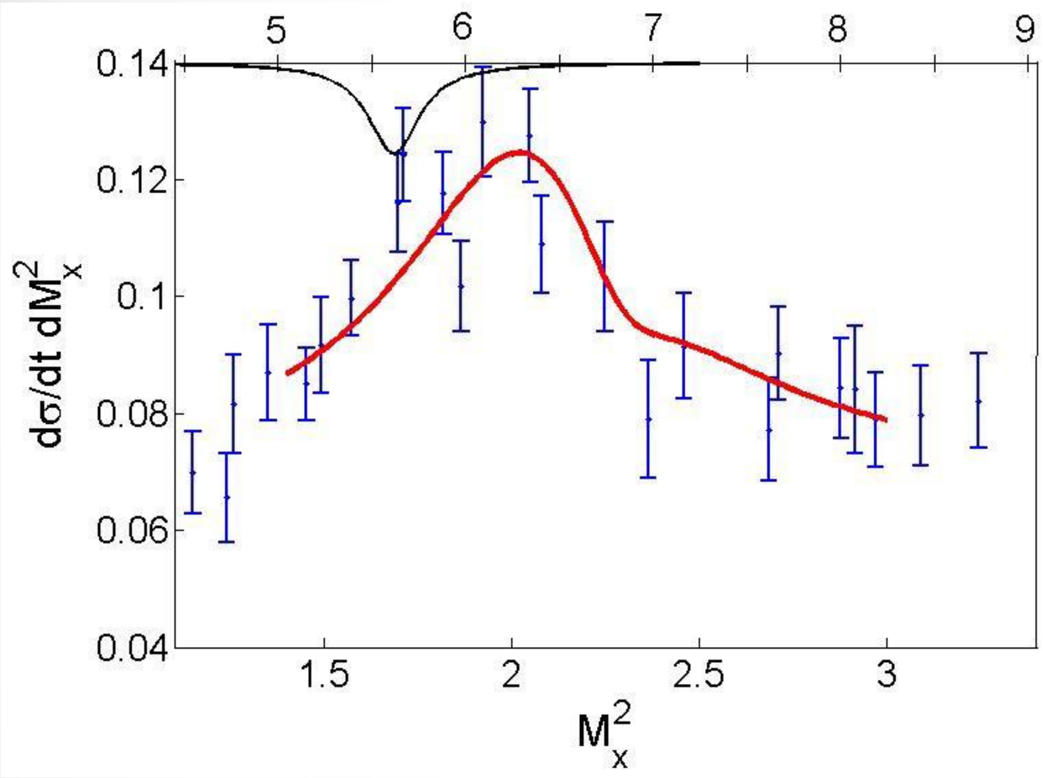


Interpretation: the peak corresponding to angle of emission of the recoil deuteron equal to 77.45° is **elastic deuteron-deuteron scattering**. The emission angle at 75.35° is the processes of **quasi-free knockout of a nucleon from the incident deuteron by the recoil deuteron.**

*) *A.M. Baldin et al. Differential Elastic Proton-Proton, Nucleon-Deuteron and Deuteron-Deuteron Scatterings at Big Transfer Momenta*, JINR Communication, 1-12397, 1979

A brilliant guess.

Baldin- Stavinskiy et al.



$d+d \rightarrow X+d$

$P = 8.9$ GeV

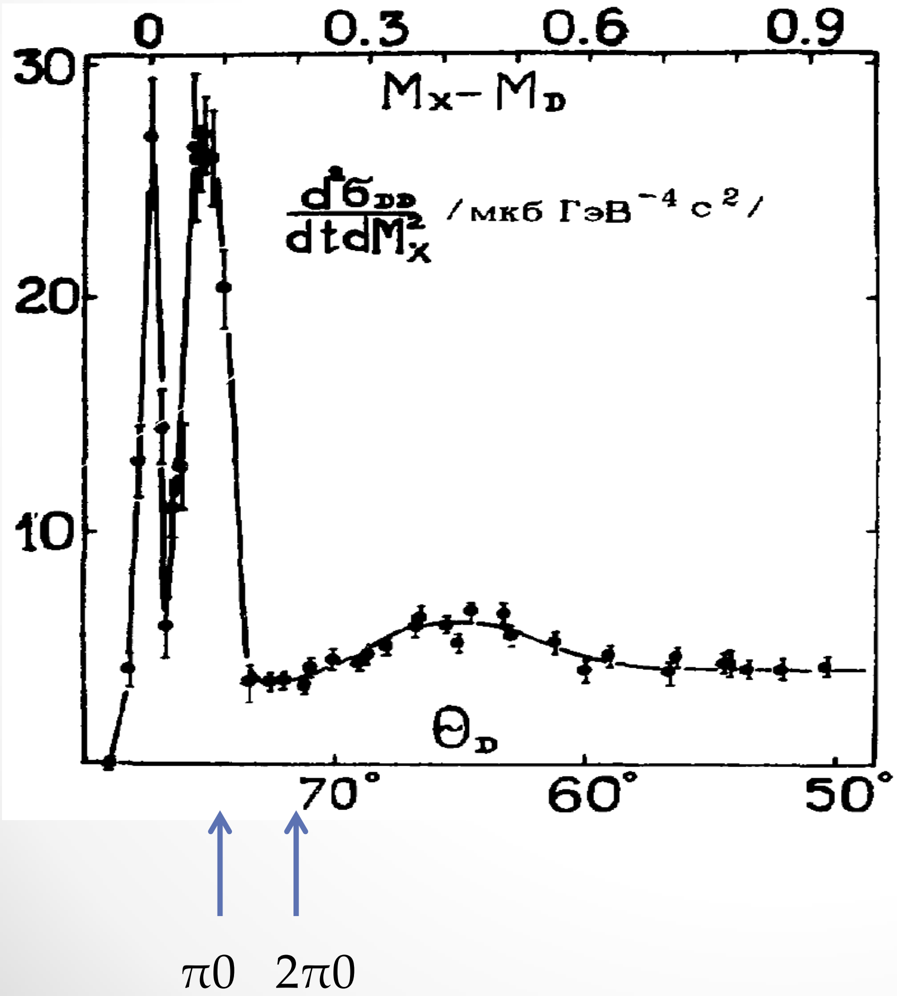
$t = -0.5$ GeV^2

Red line - calculations by B.F.K. and Jan Pribish,
model
N(1440)+N(1520)+ N(1535),
Baldin ISHEPP XXII, 2014

Black line –results of WASA-at-COSY:
M=2.37 GeV, Γ=0.07 GeV

Problem 2:

Could there be light dibaryons in the second peak region?



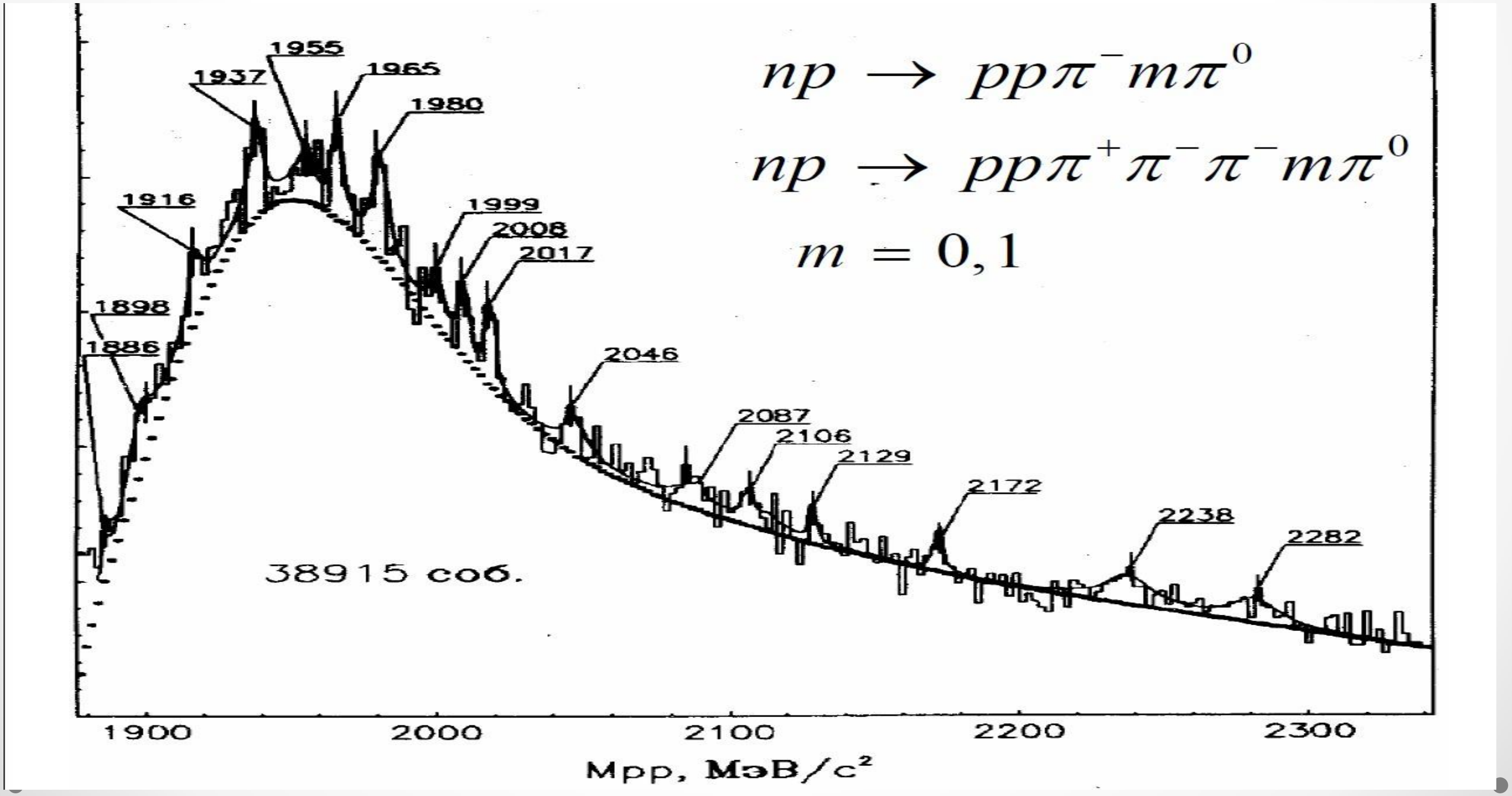
Single scale for all peaks as an invitation to ask the question.

Threshold for the production of π0 corresponds to the emission angle of the recoil deuteron ≈74.4°, and for 2π0 ≈71.7°.

Dibaryons below pion production threshold?

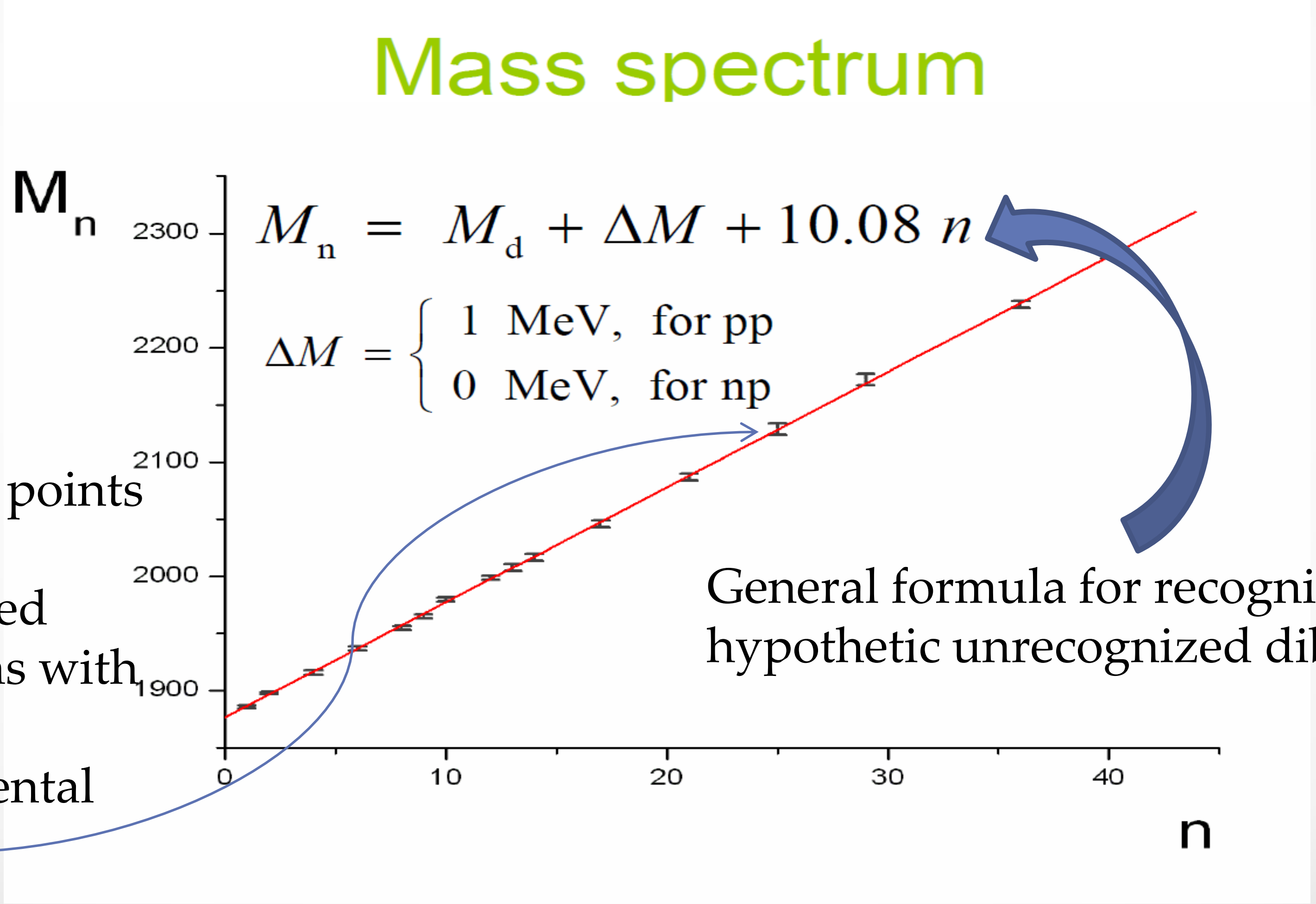
An experiment with dibaryons below pion production threshold

Yu.A. Troyan, Fiz. Elem. Chastits At. Yadra 24, 683 (1993)



Assumption:

Some dibaryons could be **unrecognized** due to a large background of extraneous events



Separate points are the recognized dibaryons with their experimental errors

General formula for recognized and hypothetic unrecognized dibaryons

Problem 3:

A mysterious connection of Baldin-Stavinskiy's and Troyan's papers

Reaction	KAM	dibaryon masses
X+D→Y+D	1886→1966	1886, 1966
	1896→1977	1896, 1976
	1916→1998	1916, 1997
	1926→2009	1926, 2007
	1936→2019	1936, 2017
	1946→2030	1946, 2027
	1997→2084	1997, 2087
	2007→2095	2007, 2097
	2017→2105	2017, 2107
	2027→2116	2027, 2118
	2037→2127	2037, 2128
	2047→2137	2047, 2138
	2057→2148	2057, 2148
	2067→2158	2067, 2158
	2077→2169	2077, 2168
	2087→2179	2087, 2178
	2097→2190	2097, 2188
	2107→2200	2107, 2198

See details in B.F.K.,J. Pribish, Baldin ISHEPP XXII, 2014

The second peak

All dibaryons in the range from 1886 to 2198 MeV/c^2 may be met in deuteron

Problem 3:

A mysterious connection of Baldin-Stavinskiy's and Troyan's papers

Reaction	KAM	dibaryon masses
X+D→Y+D	1916→1884	1916, 1886
	1926→1895	1926, 1896
	1936→1905	1936, 1906
	1946→1916	1946, 1916
	1956→1927	1956, 1926
	1966→1938	1966, 1936
	1976→1948	1976, 1946
	1986→1959	1986, 1956
	2047→2024	2047, 2027
	2057→2034	2057, 2037
	2067→2045	2067, 2047
	2077→2056	2077, 2057
	2087→2066	2087, 2067
	2097→2078	2097, 2077
	2107→2087	2107, 2087
	2118→2099	2118, 2097
	2128→2109	2128, 2107
	2138→2120	2138, 2118
	2148→2131	2148, 2128
	2158→2141	2158, 2138

Total correspondence Between Troyan's and Baldin's group data!

The first peak

KAM – kinematically allowed masses,
dibaryon masses – according to

$$M_n = M_d + 10.08\, n$$

Can this be considered as a confirmation of the existence of Troyan's dibaryons?

Toward Problem 4: Color transparency

S. J. Brodsky, A.H. Mueller, 1982

The recoil proton in large momentum transfer electron-proton scattering is produced as a small color singlet three-quark state of transverse size $b_\perp \sim 1/Q$. Because of the cancellation of gluonic interactions with wavelength smaller than $b_\perp$, such a small color-singlet hadronic state will propagate through the nucleus with a **small cross section for interacting in either elastically or inelastically**.

STANLEY J. BRODSKY, COLOR TRANSPARENCY AND THE STRUCTURE OF THE PROTON IN QUANTUM CHROMODYNAMICS, SLAC-PUB-5082, 1989

The usual method of investigation

Elastic p-p scattering in nuclear targets with different nuclear numbers *A*. **Nuclear** transparency:

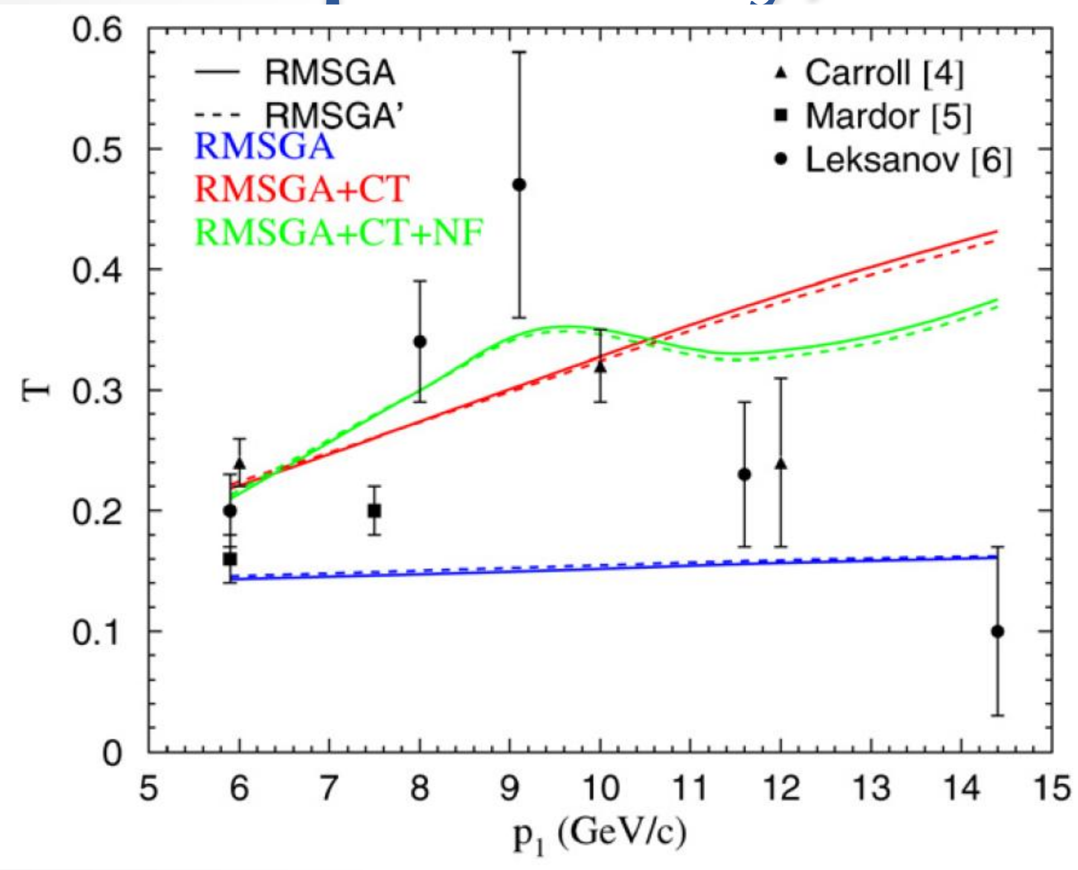
$$T(s) = \left. \frac{d\sigma(h_1 A \to h_1' h_2' (A - h_2) / dt}{A d\sigma(h_1 h_2 \to A h_1' h_2') / dt} \right|_{\theta \approx 90^\circ \text{c.m.}}$$

Problem 4:

Initial and final state interaction for hadron-proton scattering inside nucleus

The hard hadron-nucleus interaction can be more complicated in contrast with the hard lepton-nucleus scattering because of multiple rescattaring effects of quarks of a colliding hadron. It was also pointed out in [J.P. Ralston, B. Pire, Phys. Rev. Lett. 61 (1988) 1823] that an energy-dependent "chromo-Coulomb" phase shift appears in the amplitude of hadron-nucleus scattering due to the initial and final state interactions. At the same time, theories of these and other soft interactions are based only on plausible arguments and contain adjustable parameters that are not convincing enough to suggest they allow the direct experimental study of the color transparency.

Attenuation of nuclear transparency, an example



The nuclear transparency for the $^{12}C(p, 2p)$ reaction as a function of the incoming lab momentum p_1.

RMSGA – relativistic multiple-scattering Glauber approximation, CT and NF – account of the color transparency effect and nuclear filtering, correspondingly.

B. Van Overmeire, J. Ryckebusch Phys. Lett. B 644 (2007) 304

The calculations are very complex and not obvious! ⇒ **NT is not a good characteristic for describing CT.**

Current status of the problem

The process of hard scattering of protons by nuclei is rather complicated. Attempts to elucidate the existence of color transparency by studying the A-dependence of the secondary hadron yield do not make it possible to unambiguously answer the question of the nature of this dependence. It is still unclear whether it is really due to the effect of color transparency or some other reasons (Fermi-motion, initial and final state interactions, nucleon-nucleon correlations, or formation of multiquark clusters). Moreover, there is a <u>disagreement on a number of fundamental issues</u>. For example, does soft scattering of an incident particle affect its subsequent hard scattering? So according to Efremov, Kim and Lykasov [Yadernaya Fizika 44 (1986) 241]] - no, but according to Larionov, Gillitzer and Strikman [arXiv: 1905.10419v2 [nucl-th]] - yes.

New method of CT study – advantege of d+d and d+p reactions

<u>Turn the enemy into a friend:</u>

The final state interaction can be used to estimate the CT effect.

Formation time and formation length: $\tau_F \approx \frac{r_H}{k_q} E_H, \quad L_F = \tau_F V_H,$

(S. J. Brodsky, A.H. Mueller, Phys. Lett. B 206 (1988) 585)

The longer the formation length, the less frequent interactions in the final state.

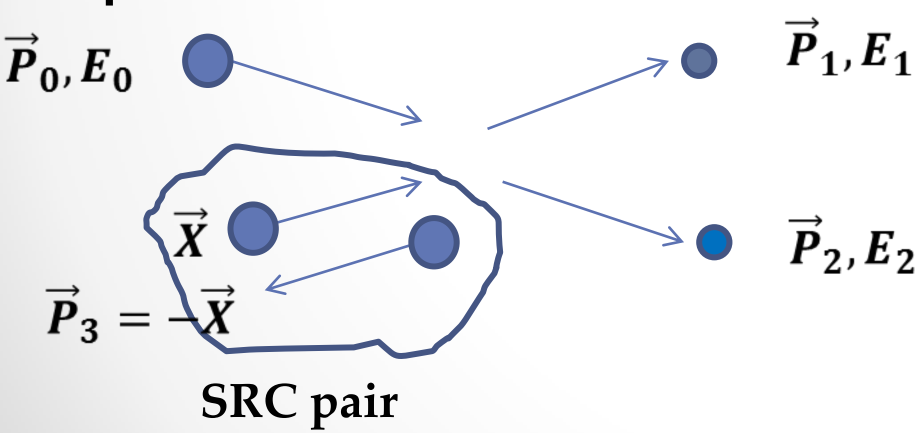
All interactions, both hard and soft, are seen now directly in the characteristics of secondary particles, due to their small number. In fact, it is only necessary to control the quasi-freedom of hard knocking out.

NICA SPD as a microscope for observing soft scatterings

How many angels are sitting on the tip of the needle?

There are many theoretical papers proving the need to take into account soft interactions which occur both before and after the hard scattering. However, there is no experimental work in which these interactions would be observed directly.

Direct control of the accuracy with which the assumption of quasi-free knockout is valid:



$$E_x = E_1 + E_2 - E_0$$

$$|P_3| = |-X| = \sqrt{E_X^2 - m_X^2}$$

The deviation of the momentum of the spectator nucleon from the calculated value characterizes the deviation of the knockout from the quasi-free one.

- With an increase in color transparency, the interaction in the final state should decrease and the quasi-free knockout criterion should be better fulfilled.

The off-shell effect

A virtual state in which one of two bound nucleons is off-shell.

Relativistic spectator formalism: see

R. Gilman, F. Gross, J. Phys. G 28 (2002) R37– R116

and references therein.

The effect can manifest themselves as fluctuations of the observed spectator nucleon energy around the calculated one.

Let's now go back to **virtual states** of a different type - those that **could be observed in the Baldin-Stavinskiy and Troyan experiments**.

Attenuation of color transparency, a forerunner to the theory

Landshoff model for for elastic scattering at wide angle (Phys. Rev. D 10 (1974) 1024):

1) hadrons consist of constituents on the mass shell,

2) all the constituents scatter through nearly the same angle, so that they can readily recombine to form the final-state hadrons.

This results in: the differential cross sections calculated from the model have energy dependences that do not agree with those which would be obtained from the usual quark counting. They turn out to be larger.

Attenuation of color transparency, explanation

Ralston and Pire, Phys. Rev. Lett. 61 (1988)1823

In pQCD, each scattered quark propagator is someplace off shell by order 1/s and namely this fact leads to the usual quark counting rules. However, there is a class of diagrams, pointed out by Lanshoff, in which independent hard scatterings occur with no far-of shell quarks. The amplitude for such processes increase if more impact parameter space is available, i. e. if the protons are "large". Thus, if the transverse coordinate space available for collisions of quarks increases then the amplitude is large. This results in oscillatory energy dependence for nuclear transparency.

Brodsky and de Teramond explanation of the attenuation

Phys. Rev. Lett. 60 (1988)1924

In leading order in $1/p_{\perp}$, only the lower-particle-number valence quarks with all the quarks within an impact distance $b_{\perp} < 1/p_{\perp}$ contribute to the high-momentum transfer scattering amplitude in QCD. Such component of wave function has a small dipole momentum and thus according pQCD interacts only weakly. This is the color transparency.

Attenuation of color transparency may be explained by excitation of resonance-like structure in s-channel. Such resonances couple to fully interacting large-scale structure of the proton.

Brodsky and de Teramond explanation of the attenuation

Among such excitations there can be multigluon excitations and excitations of 6-quark systems with hidden color, as well as excitations of quark-antiquark pairs $|6q(q\overline{q})\rangle, |6q2(q\overline{q})\rangle, \ldots$.
Since the authors consider an attraction between such q and $\overline{q}$ with constituent quarks as interaction of ordinary particles that satisfy the $1/v_{rel}$ law, where v_{rel} is relative velocity of interacting constituent and see quarks (or antiquarks), all valence and sea quarks are assumed to be <u>on the mass shell</u>.

Therefore, such quark-antiquark excitations should be observed as light dibaryons in the region below the pion production threshold.

<u>Assumption</u>: It is these dibaryons that could show themselves in the experiments of Baldin-Stavinskiy and Troyan !

<u>Proposal</u>: Let's check this at NICA SPD.

What should be observed

After collecting the required number of events d+d→n+p+d for a given value of $\sqrt{s}$, the next data processing is performed:

select sets of events that correspond to some fixed intervals of the Mandelstam variable *t*. Then, in each of these intervals, we sort the events according to whether they are quasi-free or not. The ratio of the number of quasi-free events to their total number will characterize the value of the color transparency of d, n and p in a selected kinematic region. It is desirable to carry out such an estimate for events with the effective mass of the n-p system both below the threshold for pion production and above it (but in events without pion production).

Then we check the presence of the Troyan dibaryons in events in which are not quasi-free. If such dibaryons exist, we should check existence of a positive correlation between observation of the dibaryons and the absence of quasi-free knockout for testing the Brodsky – de Teramond explanation of the color transparency.

Along t: from nucleons and mesons to quarks and gluons

Luminosity 10^{27} cm^{-2} s^{-1}

$\sqrt{s}=6.7 \leftrightarrow P_D = 10.1$ GeV/c

1 mkb = 10^{-30} cm^2

P_D = 8,9 ГэВ/с	
$-t$ (ГэВ/с)^2	$\frac{d\sigma}{dt}$ (DD → DD) мб·ГэВ$^{-2}$·с^2
0,282 ± 0,01	(12 ± 2) · 10^{-2}
0,495 ± 0,015	(5,4 ± 0,4) · 10^{-2}
0,768 ± 0,02	(2,2 ± 0,2) · 10^{-2}
1,12 ± 0,03	(5,8 ± 0,7) · 10^{-3}
1,32 ± 0,04	(4,2 ± 0,4) · 10^{-3}
1,63 ± 0,05	(1,7 ± 0,2) · 10^{-3}
1,97 ± 0,05	(0,46 ± 0,16) · 10^{-3}

Δσ (mkb)
2.400±0.400
1.620±0.100
0.880±0.040
0.348±0.042
0.336±0.016
0.170±0.020
0.055±0.019

Number of events
$24 \cdot 10^3$
$16.2 \cdot 10^3$
$8.8 \cdot 10^3$
$3.48 \cdot 10^3$
$3.36 \cdot 10^3$
$1.7 \cdot 10^3$
$0.55 \cdot 10^3$

$b_\perp \leq 0.14$ fm (see slide 25)

4 month=10^7sec

Baldin-Stavinskiy experiment, peak №1

NICA SPD, peak №2

Feasibility at maximum beam energy

$\sqrt{s}$ = 53 GeV	
$-t$ (GeV^2)	$d\sigma/dt$ (μb/GeV^2)
0.55	8.70
0.59	5.24
0.65	4.82
0.73	3.01
0.81	1.88
0.89	0.80
0.97	0.84
1.09	0.36
1.25	0.20
1.40	0.07

ISR data (d+d→d+d)

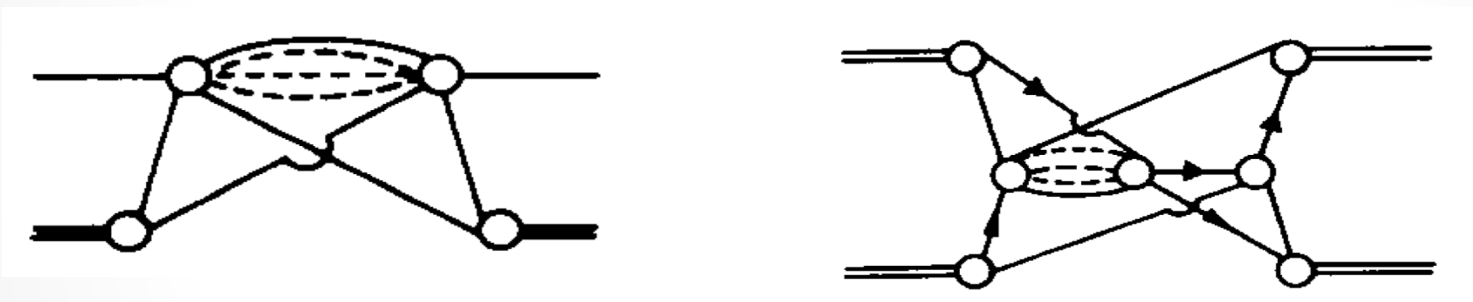
$N_{ev}=35\cdot10^3$ – lower bound for number of events during 1 month in region of the first peak for NICA SPD at $\sqrt{s}$=28 GeV and $-t$ =1.40±0.05 for luminosity $2\cdot10^{30}$ cm^{-2} s^{-1}.

A comparison with the previous table for Baldin-Stavinskiy experiment shows that an increase in luminosity with increasing beam energy not only compensates a decrease in the cross section for bigger √s, but also gives an increase in the number of events by at least a factor of 100 at the maximum beam energy.
Therefore, it will be possible to advance into a region of significantly higher values of |t| at the NICA SPD than in the Baldin -Stavinskiy experiment.

NICA SPD

Why region of not very large √s but high |t| may be interesting too

The Glauber multiple-scattering theory can explain elastic d-d scattering only for |t|<0.4 GeV. Intermediate production of particles can occur for higher |t|, G. Goggi et al, Nucl. Phys. B149 (1979) 381.



Double and triple scattering with intermediate particles

This is consistent with our explanation for the existence of the peaks based on the color transparency attenuation models. For $|t|=0.5$ GeV^2, $\Delta p=0.72$ GeV, $\Delta x=0.27$ fm => density in the deuteron at the moment of collision may exceed one in the center of heavy nuclei by **137** times! The similarity with phase transitions in dense cold nuclear matter is obvious.

Why region of not very large $\sqrt{s}$ but high $|t|$ may be interesting too

In fact, the processes observed in the Baldin-Stavinskiy experiment, among other things, represent the **direct knocking out of the Blokhintsev fluctuon*)** from the target deuteron by one of the nucleons of the incident deuteron (see slide 28). Indeed, the **Butler-Pearson mechanism** [Phys. Lett. 1 (1962) 77] of combining cascade nucleons into deuterons inside a nucleus is impossible in this case due to the absence of all the elements of the system necessary for this. At the same time, the properties of the fluctuon, including the dependence of its interaction cross section on the transferred momentum, have never been studied.

*) Д.И. Блохинцев, ЖЭТФ, т.33, вып. 5

Pitfall № 1

In contrast to the Baldin– Stavinskiy experiment, now it is necessary to register two nucleons in the final state, which is a problem in itself. However, the NICA SPD unique detectors with ΔΩ~ 4π geometry and possibility of detection of all kinds of particles allow, in principle, to fulfill the experiment.
This circumstance can lead to some losses in number of the observed events.

Pitfall № 2

Recognizing quasi-free knockout requires a very accurate measurement of the momenta of all particles in the final state.

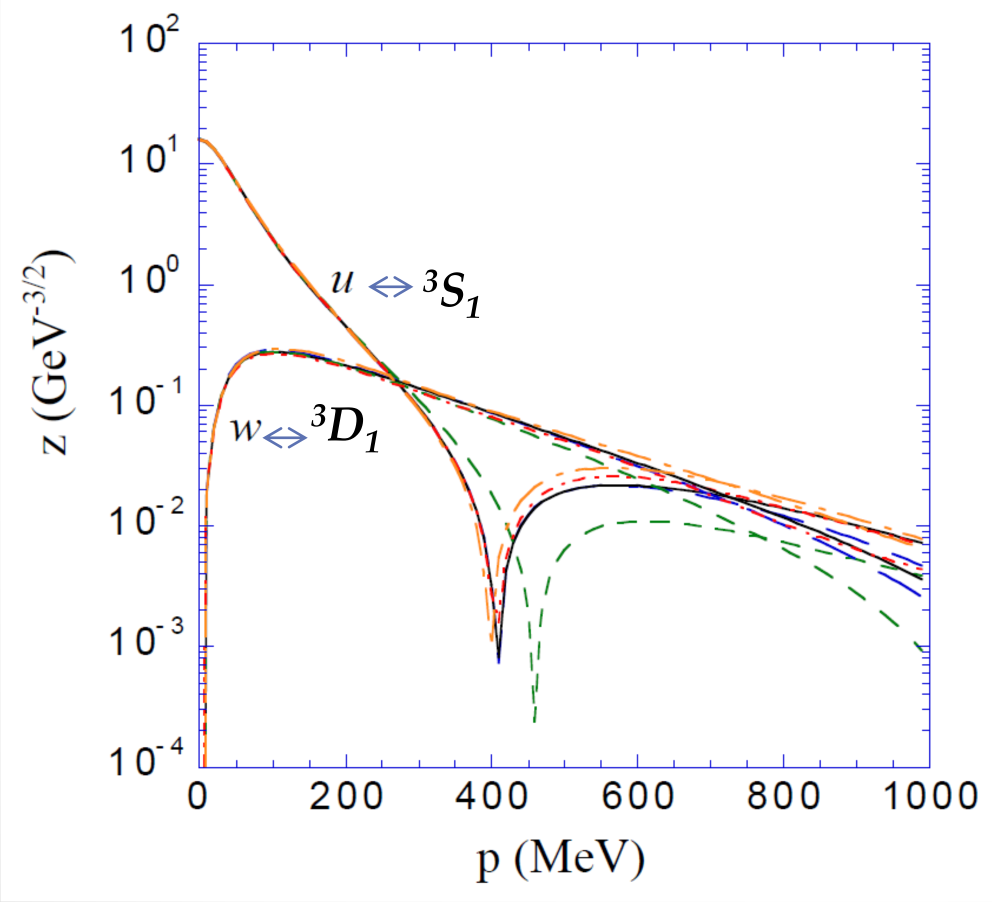
There are two ways to solve this problem:

The first, more reliable one can be used if the planned value of $\Delta p / p = 10^{-5}$ is reached. In this case, quasi-free knockout can be recognized using the laws of conservation of energy and momentum from the measured momenta of secondary particles (see slide 21).

The second method is reduced to an accurate measurement of the projections of the momentum of all particles in the transverse plane. Quasi-free knockout is recognized by how many nucleons balance the momentum of the scattered deuteron - one or two. However, the above-cited publication of Jlab Hall A Collaborations (see slide 3) implies that this approach is dangerous.

Measurement of the deuteron wave function

Importance: testing different potentials of N-N interactions and different models of deuteron.



Momentum space wave functions for five models: AV18 (solid), Paris (long dashed), CD Bonn (short dashed), IIB (short dotdashed), and W16 (long dot-dashed).

R. Gilman, Franz Gross,
J. Phys. G: Nucl. Part. Phys. 2002 R37

IIB and W16 – **relativistic** models taking into account the **off-shell effects** and a contribution of a virtual ***P*-state** (in addition to *S*- and *D*-waves).

Let's remember

Quantum numbers of deuteron $I(J^P) = 0(1^+)$ are consistent with two its inner two-nucleon states corresponding to $L=0$, $S=1$ and $L=2$, $S=1$, which are denoted as $^3S_1$ and $^3D_1$, accordingly.

In the both cases, the spatial and spin parts of the total wave function are symmetric with respect to permutation of nucleons, while the isospin ones are antisymmetric.

The spatial part of wave function of deuteron

The spatial part of wave function of $^3S_1$ state, $R_0(r)\ Y_{00}\ (\theta,\varphi)$, is isotropic.

The spatial part of $^3S_1$ state:

$$3 \otimes 5 = 3 \oplus 5 \oplus 7$$

Triplet in the decomposition corresponds to the total angular momentum ***J*** of deuteron equal to **1, as it should be**. Omitting the common factor $R_2(r)$ describing radial part of wave function, we can write angular dependence of $^3D_1$ state (using the Clebsch-Gordan coefficients of the decomposition of the direct product)

$$\psi_{+1}(\theta,\phi) = \sqrt{\frac{3}{5}}Y_{2,+2}(\theta,\phi)\chi_{-1} - \sqrt{\frac{3}{10}}Y_{2,+1}(\theta,\phi)\chi_0 + \sqrt{\frac{1}{10}}Y_{2,0}(\theta,\phi)\chi_{+1},$$

$$\psi_{0}(\theta,\phi) = \sqrt{\frac{3}{10}}Y_{2,+1}(\theta,\phi)\chi_{-1} - \sqrt{\frac{2}{5}}Y_{2,0}(\theta,\phi)\chi_0 + \sqrt{\frac{3}{10}}Y_{2,-1}(\theta,\phi)\chi_{+1},$$

$$\psi_{-1}(\theta,\phi) = \sqrt{\frac{1}{10}}Y_{2,0}(\theta,\phi)\chi_{-1} - \sqrt{\frac{3}{10}}Y_{2,-1}(\theta,\phi)\chi_0 + \sqrt{\frac{3}{5}}Y_{2,-2}(\theta,\phi)\chi_{+1}.$$

Here **indexes of ψ and χ** describe values of J_z and S_z, correspondingly.

Quasi-free knockout assumption

– means that angular and momentum distributions of the nucleon-spectator are determined by its intranuclear wave function.

In particular, the **conditional probability** to observe a secondary nucleon with momentum *p* is determined by squared absolute value of Fourier transform of $R_0(p)$ or $R_2(p)$. To find the **overall probability**, it is necessary to multiply the conditional probability by an **interaction probability** of a projectile with the first nucleon of the pair taking into account its **intranuclear momentum**. For hard processes, the latter is well approximated using the **quark counting rules.**

Thus, the wave function of the deuteron can be studied in events satisfying the condition of quasi-free knockout (see slide 21).

How to distinguish S-wave from D-wave experimentally?

$$\psi_{+1}(\theta,\phi)=\sqrt{\frac{3}{5}}Y_{2,+2}(\theta,\phi)\chi_{-1}-\sqrt{\frac{3}{10}}Y_{2,+1}(\theta,\phi)\chi_{0}+\sqrt{\frac{1}{10}}Y_{2,0}(\theta,\phi)\chi_{+1}$$

The first method (measurement of polarization):

For S-states polarized along the z axis, projections of spins of all deuterons are directed **along** the z axis.

For D-states polarized along the z axis, spins of **60%** of deuterons are directed in the **opposite** direction to the direction of the z axis – see the first term in expression for $\psi_{+1}(\theta,\phi)$.

Consequence:

All nucleons-spectators emitted from the deuteron, which was in the S-state before the collision, are polarized **along** the z-axis,

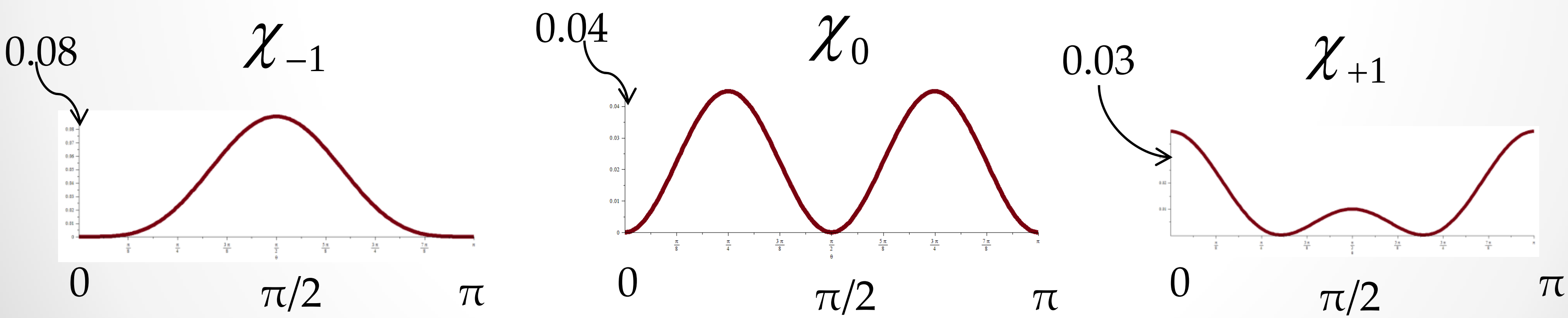
60% of nucleons-spectators emitted from the deuteron, which was in the D-state before the interaction, are polarized **against** the z-axis.

How to distinguish S-wave from D-wave experimentally?

The second method (by angular distribution). The S-wave is isotropic.

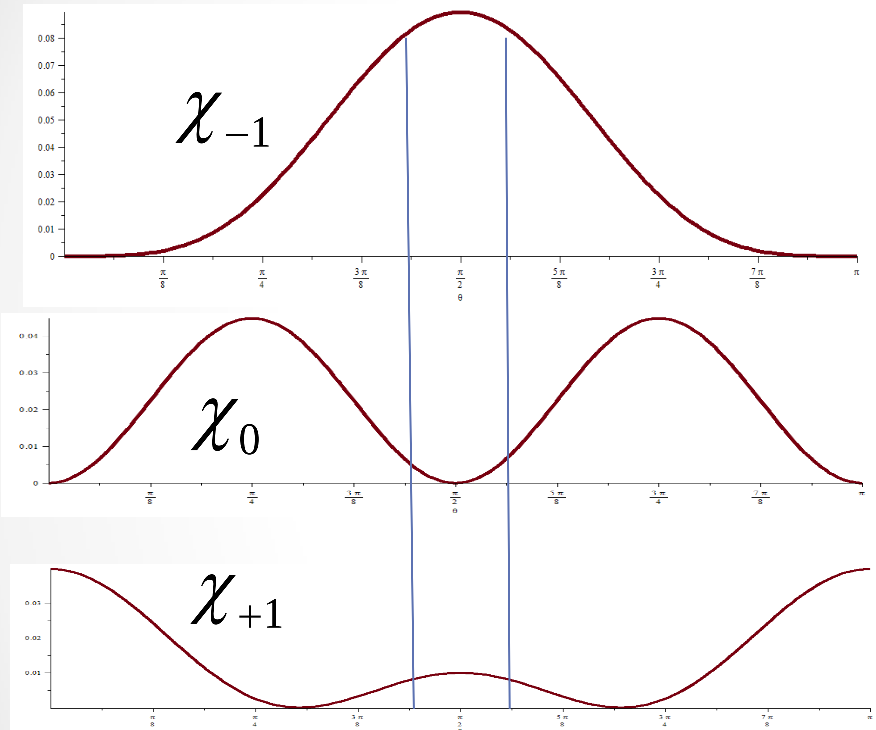
$$|Y_{2,+2}(\theta,\phi)|^2 = \frac{15}{32\pi}\sin^4\theta, \quad |Y_{2,+1}(\theta,\phi)|^2 = \frac{15}{8\pi}\cos^2\theta\sin^2\theta, \quad |Y_{2,0}(\theta,\phi)|^2 = \frac{5}{16\pi}(1-3\cos^2\theta)^2$$

For nucleons polarized against the z-axis, perpendicular to it, polarized along it.



χ_0 **– dangerous component which gives a false contribution to events with negative polarization of spectator nucleons.**

Optimal angles of registration of spectator nucleons



$$\frac{\pi}{2} \pm \frac{\pi}{16}$$

The probability of falling into the interval of polar angles $\theta = \frac{\pi}{2} \pm \frac{\pi}{16}$ **at any azimuthal one:**
nucleons in the S-state $P_S = 0.195$,
nucleons in the D-state $P_D = 0.214$.

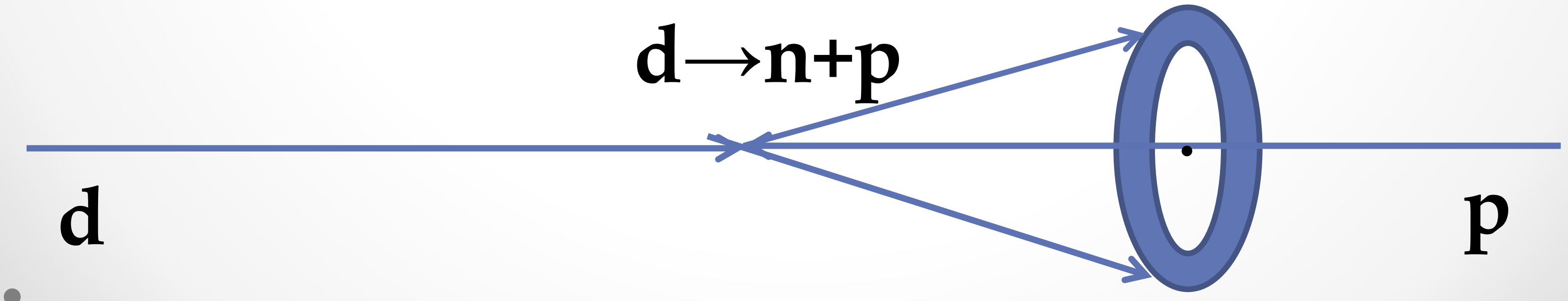
Transversely polarized states that create an error in measuring the number of events with negative polarization of spectator nucleons are strongly suppressed. Furthemore, relative probabilities of observation for all values of the nucleon polarization at a given observation angle can be exactly calculated and taken into account.

Polarization characteristics of the deuteron beam

Polarization of the deuteron beam may be either transverse or longitudinal. It is important that this direction is strictly fixed and accurately measured. Also, the density matrix for the polarization states must be accurately measured in a Gerlach-Stern type experiment,

$$\varrho = diag(p_+, p_0, p_-) \;.$$

We can use a system of detectors of secondary nucleons arranged along a ring perpendicular to the direction of the beam and passing through the center of the ring to increase statistics if a number of quasi-free knockouts turns out to be small.



Thanks for your attention!