On the possibility of observing weakly excited 6-quark states in d-d → 6q+d processes at the NICA SPD

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Annotation

1. **Some possible manifestations of quark degrees of freedom in nuclear physics**
2. **Registration of dibaryons in collinear kinematics at the NICA SPD**
3. **Challenges for the near future**

1. The Problem

Observation weakly excited (below π production threshold) deuteron states in d-d → d*+d reactions at the colliding beams of the NICA SPD facility at JINR.

For what? Experimental detection of possible transformations in small-nucleon systems.

This may provide clues to understanding phase transitions in nuclear matter.

Two types of dibaryons

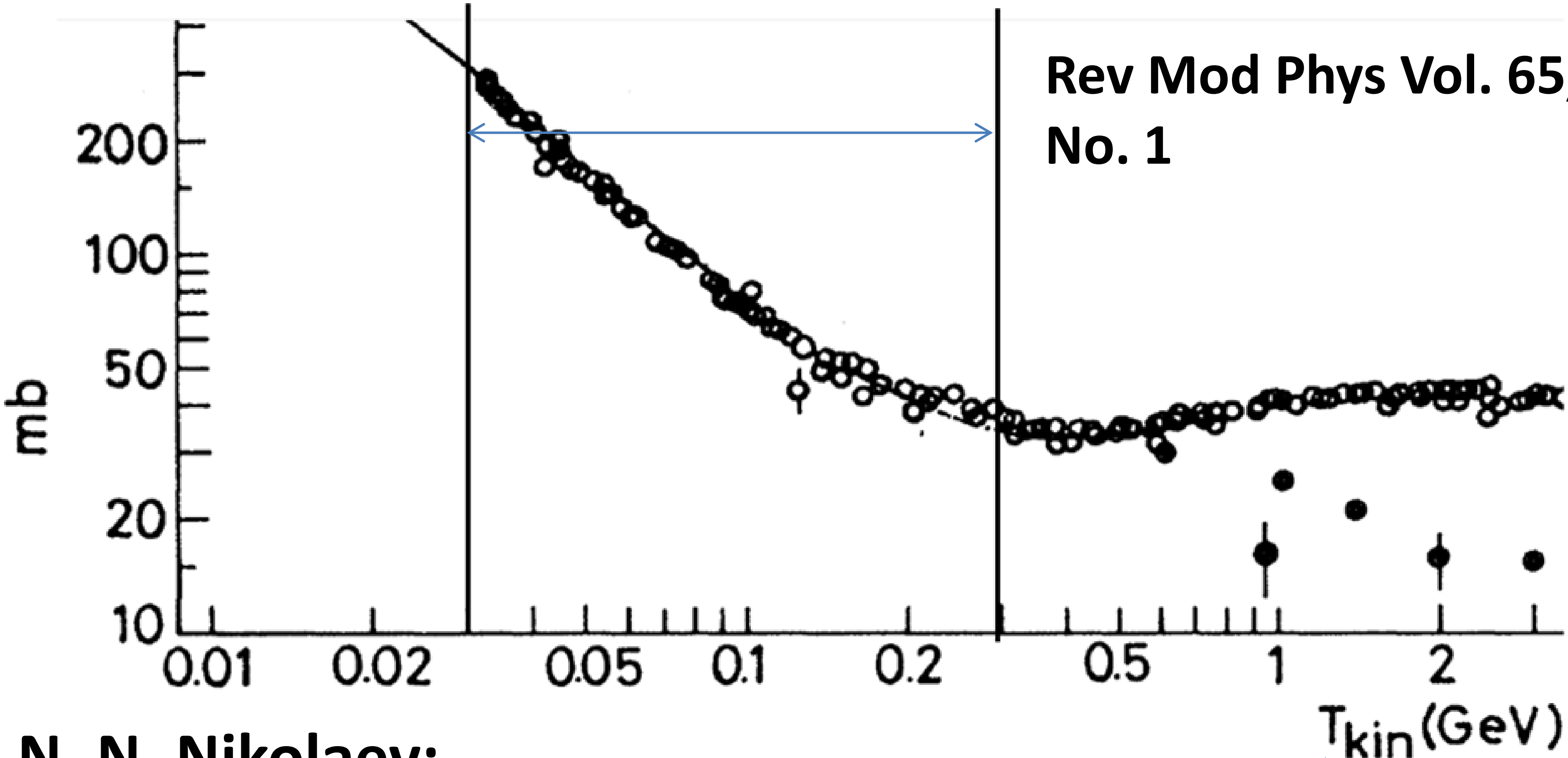
1. Six-quark systems possessing definite quantum numbers (among them mass, decay width, baryon number, spatial parity), as is the case for meson or baryon resonances

[Ю.А. Троян, ЭЧАЯ (1993)].

2. Small pieces of quark-gluon plasma, whose properties depend on the temperature inside them

(see below).

Is it possible: n+p -> d*->n+p?



Rev Mod Phys Vol. 65, No. 1

N. N. Nikolaev:
"No resonance n-p peaks are seen in the dibaryon excitation region"

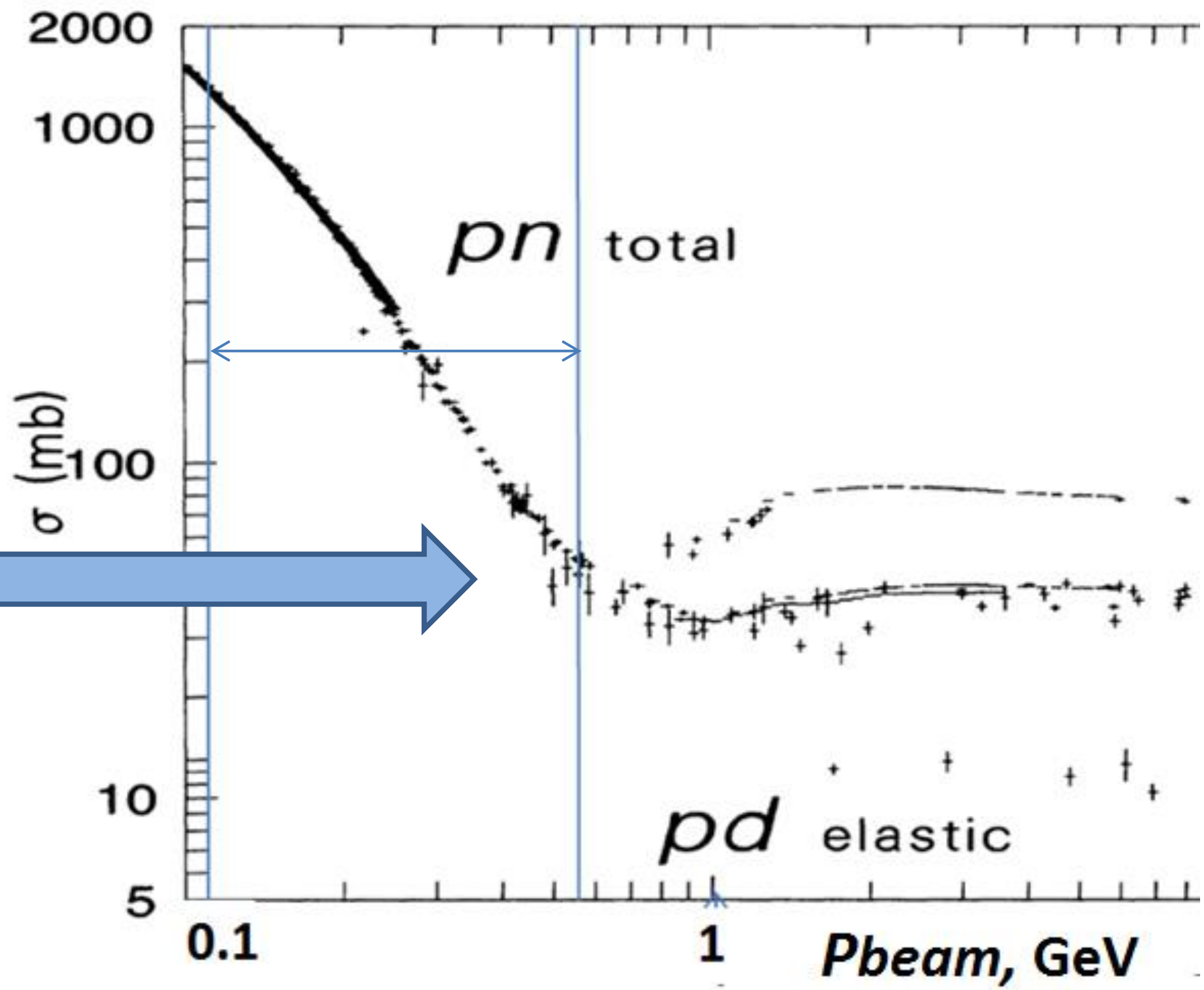
Counter-evidence: "It is difficult to assess the <u>accuracy and reliability</u> of the data"

Most reliable and precise data **recommended for use by PDG in 2023**

https://pdg.lbl.gov/rpp-archive/files/PhysRevD.45.S1.pdf

From gold-bearing sand to gold

For the upper energy part of spectrum some chances for the existence of light resonant dibaryons <u>still remain</u>.

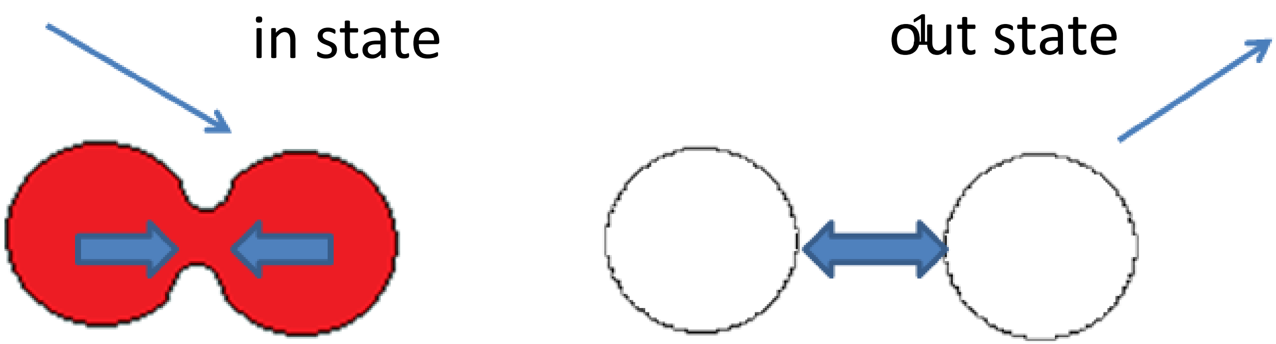


An admixture of 6q states in the deuteron may be of order 5.6 %*)

*) V. A. Matveev, P. Sorba, Lett. Nuov. Cim. 20 (1977) 435

<u>How can the 6q system behave in a collision with an accelerated particle</u>? Possible scenario:

It's only 1 fm from attraction to repulsion:



The <u>string breaking energy</u> of the 6q system inside ^{12}C nucleus is 290 MeV (see the next slide).

The colliding particle must break the gluon string by expending some energy. After breaking the gluon bond, the resulting nucleons fall into the region of the repulsive potential, well known in nuclear physics.

Experimental indication of this mechanism

PRL **99**, 072501 (2007)

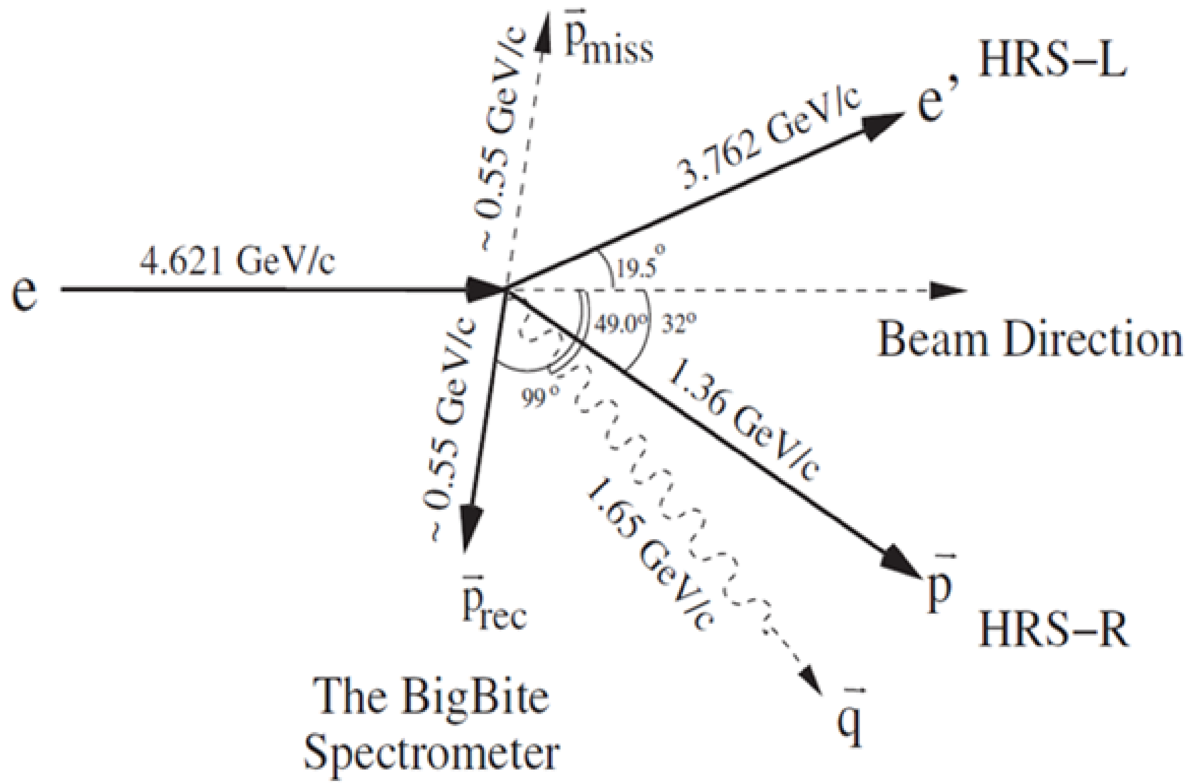
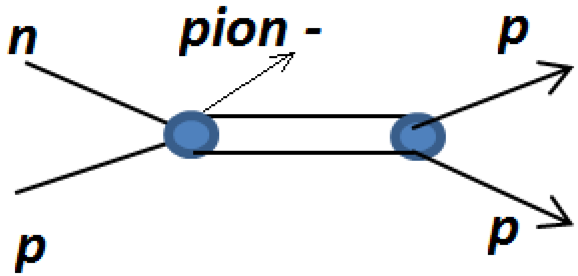


FIG. 1. A vector diagram of the layout of the $^{12}C(e, e'pp)$ experiment shown for the largest p_{miss} kinematics of 0.55 GeV/c.

The nucleons knocked out of the nucleus could not have the momenta shown in the figure before the collision, because in this case the total energy of the particles in the initial state must be 290 MeV greater than the total energy of the energy of the particles in the final state.

Weak excitation of the 6q system in deuteron

Non-resonant diproton production



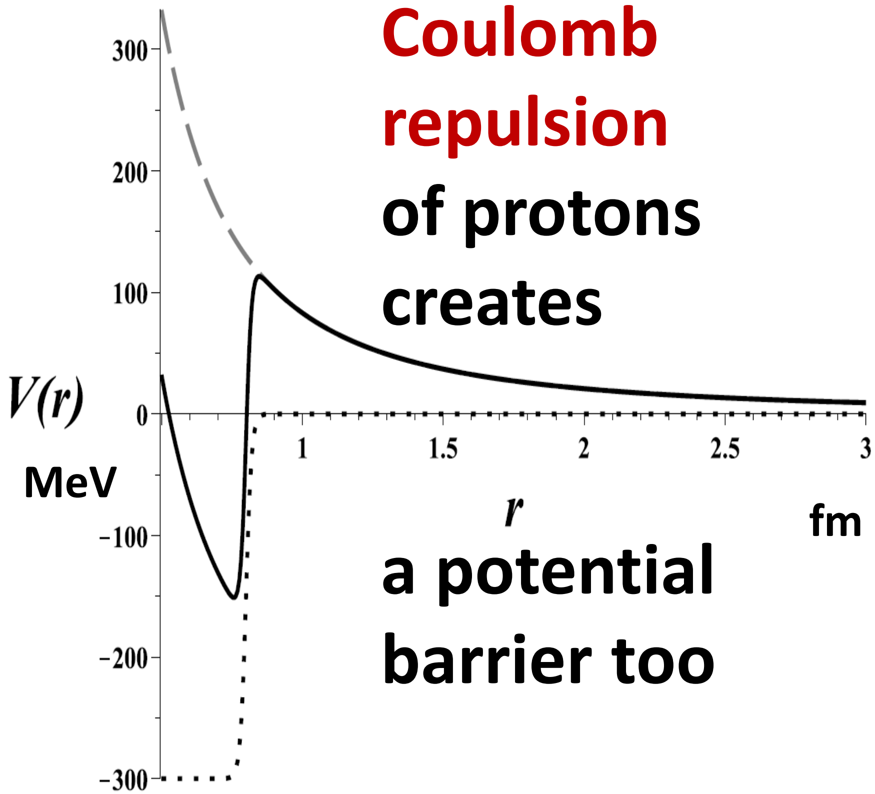
2. "Similar effects (the increase of pp-production at masses near 2 m_p) were observed before, e.g. in the nuclear reactions ^2H (d, pp) nn [Chinese Phys. Lett.]."

B. M. Abramov et al, Z. Phys. C 69, 409-413 (1996)

1. "At mass of (1877.5 ± 0.5) MeV/c^2 an irregularity is observed at the level of 6 standard deviations with a width of (2.0 ± 0.5) MeV/c."

"An attempt to explain the observed effect in terms of final state interaction (FSI), as shown in [14], encounters some problems."

Possible origin of the observed diproton state



Coulomb repulsion of protons creates a potential barrier too

1. **n+p→ π^- +2p.** The strong potential holding 2 protons in the 6q in deuteron state is taken to be of 300 MeV deep and is concentrated in a region $r \leq 1$ fm. The <u>orbital moment *L*=1 creates centri-fugal potential barrier</u> at the edge of the potential well.

2. By emitting a negative pion the 6q system excited **in the d-d collision** cools down and passes to a weakly excited six-quark state, which for some time is kept from decaying into two protons by the internal **centrifugal+ Coulomb** barrier

Comparison of hard and soft splitting mechanisms of 6q system in deuteron

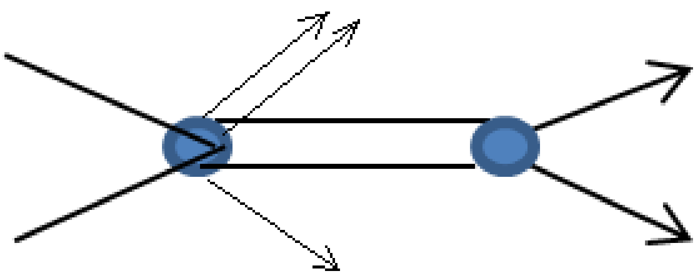
- **When the 6q system in d is splitted by a colliding particle, it is thrown over the potential barrier due to the energy released in the collision (see p. 7 & 8). The subsequent acceleration of the neutron and proton occurs due to sliding down a slope of repulsion potential of nucleons at $r \leq 1$ fm.**
- **The soft decay of the same 6q system with charge 1, present in the deuteron with some probability, occurs due to its weak excitation and transformation into the 6q system with charge 2. The subsequent decay occurs by means of the tunneling of protons through the total Coulomb and orbital repulsion potentials (see p. 9 & 10).**
- **Interestingly, both of these strange facts can be explained by assuming that the deuteron contains a small admixture of six-quark states with zero (or almost zero) excitation energy.**

Other possible dibaryons in the p-p system

«ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА»
1993, ТОМ 24, ВЫП.3

УЗКИЕ ДИПРОТОННЫЕ РЕЗОНАНСЫ

Ю.А.Троян



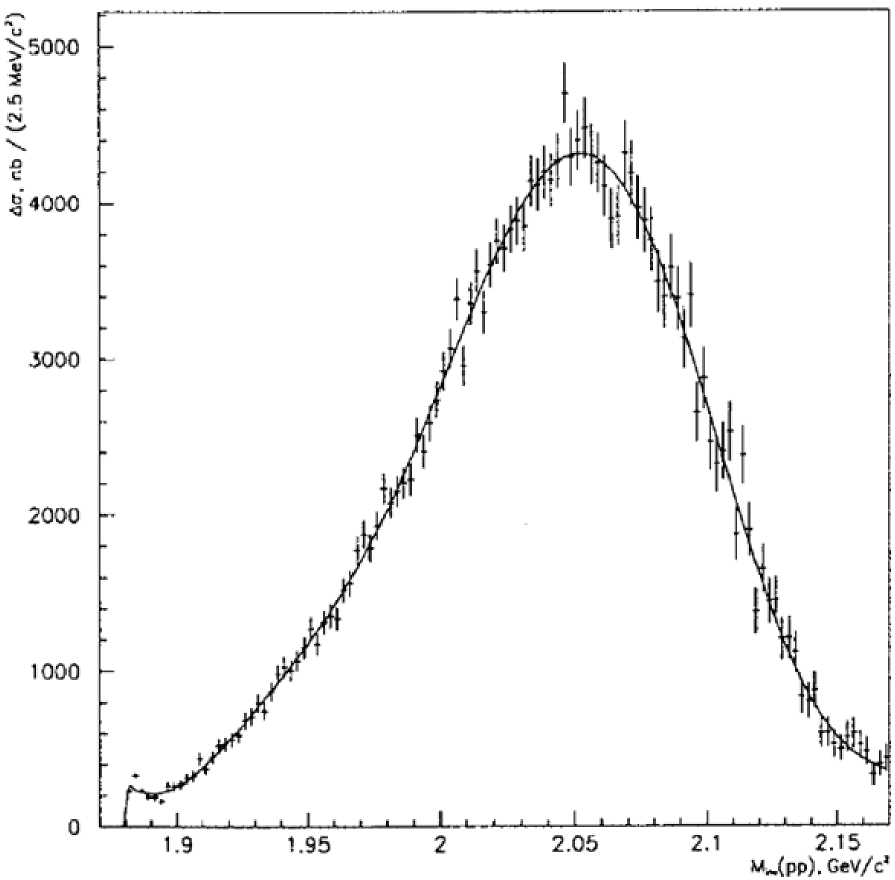
<u>Non-resonant</u> dibaryon production. Yu. A. Troyan obtained evidence for the existence of 10 light dibaryons with excitation energies from 10 to 140 MeV, which decayed into two protons.

<u>Deep cooling.</u>

<u>Number of secondary pions: from two to five</u>.

Why were these resonances not observed in the experiment of Abramov et al?

B. M. Abramov, Z. Phys. C 69, 409-413 (1996)



The $pn \to pp + \pi^-$ differential cross-section *vs* $M_{inv}(pp)$

Probably due to poor cooling: only 1 pion instead of several (from 2 to 5).
This may mean that dibaryons may resemble **small pieces of q-g plasma** more closely than ordinary baryon resonances.
Perhaps they may not have a certain mass and width, but are characterized by **temperature.**

EMC effect, Nature, 566(2019)354

Basic statement: the EMC effect on a specific atomic nucleus is determined by the abundance of SRC pairs in it. This statement can be expressed by the equality

$$\frac{n^d_{SRC}(\Delta F_2^p + \Delta F_2^n)}{F_2^d} = \frac{\frac{F_2^A}{F_2^d} - (Z-N)\frac{F_2^p}{F_2^d} - N}{(A/2)a_2 - N}, \quad (1)$$

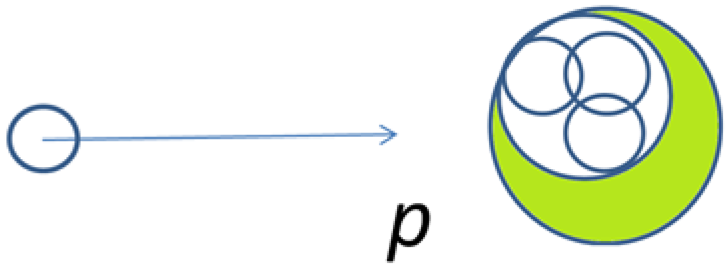
where n^d_{SRC} is a number of SRC pairs in the deuteron. However, modern experimental data are consistent with the statement that $n_d^{SRC} = 1$ within the accuracy of the model in Nature (see Appendix). Thus, the EMC effect should be connected not with the abundance of SRC pairs in the atomic nuclei, but with the amount of the quasi-deuterons in them.

⇩

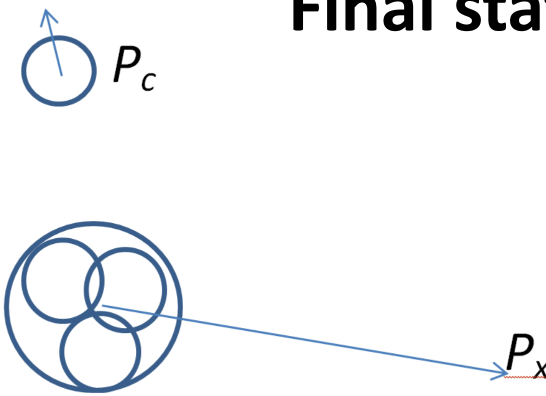
Then EMC effect itself can be explained by the admixture of the 6-q states in quasi-deutrons in atomic nuclei.

Cumulative processes

Initial state



Final state



$$\begin{cases} E + M_X = E_c + E_X, \\ \mathbf{P} = \mathbf{P}_c + \mathbf{P}_X \end{cases}$$

The exact analytical expression satisfying this system for the mass of the nuclear cluster on which elastic scattering occurred is as follows

$$M_X = (E_p E_c - M_p^2 - P_p P_c \cos\theta_c)/(E_p - E_c)$$

This formula (exact and new) allows us to determine the mass of the intranuclear object on which the scattering of the accelerated proton at an angle of 119° took place in the experiment of S.V. Boyarinov et al, ЯФ, 46 (1987) 1472.

It turned out that it was α-cluster compressed at the moment of collision to the size of h / p ~ 0.4 fm.

V.A. Matveev, P. Sorba, Nuov.Cimento A 45 (1978) 257

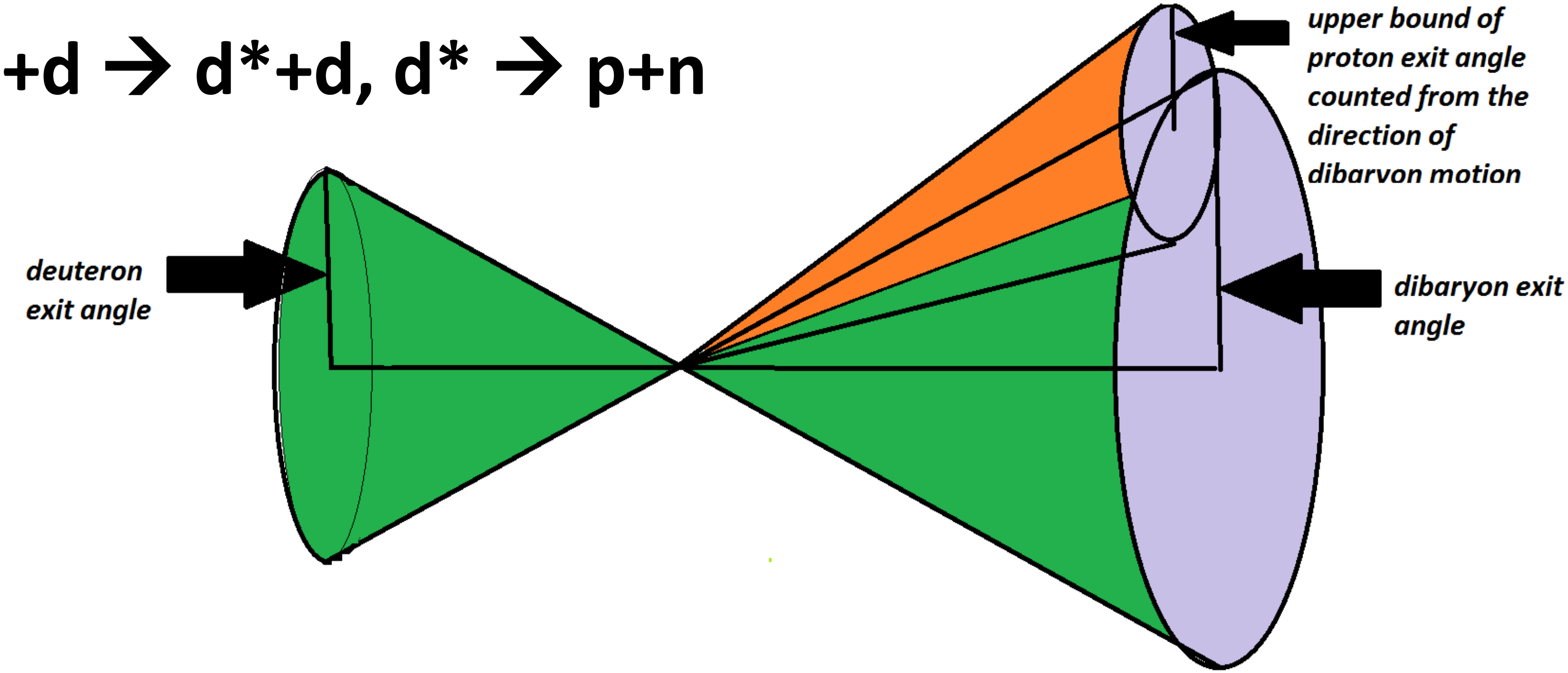
12q system!

Conclusion on the first topic of the report

- There are theoretical and experimental indications that there is an admixture of 6q states inside the deuteron. They can be split in collisions with accelerated particles with energy expenditures of the order of 300 MeV.
- There are certain reasons to believe that dibaryon resonances can be excited in colliding deuterons slightly below the pion production threshold.
- There are also experimental indications that dibaryons excited in the deuteron can be non-resonant in nature (to be characterized by temperature).
- There are experimental and theoretical indications on the possibility of the presence of other multi-quark states in nuclei: 9q, 12q and may be others for heavier nuclei.

2. Kinematic signature of dibaryon production

$d+d \rightarrow d^*+d,\ d^* \rightarrow p+n$



It is assumed that dibaryons can decay in collinear kinematics (along the direction of motion of the parent dibaryon).

Experiment in coincidence of hits d and p in counters located on opposite sides.

Results of calculations at √s=6.7, t=-0.5

Cannot be used in any way
<σ> =0.033°
Gauss distribution ↓

Great potential for experiment improvement

We need to distinguish the proton from the deuteron (TOF detector)

E_{ex} MeV	Θ_d °	P_{d}, GeV	P_{p1} GeV	P_{p2} GeV	t_d ns	t_{p1} ns	t_{p2} ns
10	14.6447	2.7723	1.537	1.233	4.025	3.905	4.188
20	14.6536	2.7689	1.613	1.154	4.026	3.856	4.296
30	14.6624	2.7655	1.668	1.096	4.028	3.824	4.387
40	14.6712	2.7620	1.712	1.048	4.029	3.801	4.473
50	14.6800	2.7586	1.751	1.006	4.031	3.781	4.558
60	14.6887	2.7551	1.785	0.968	4.032	3.766	4.642
70	14.6974	2.7516 *)	1.816	0.934	4.034	3.752	4.724
80	14.7060	2.7481	1.844	0.902	4.036	3.740	4.809
90	14.7146	2.7445	1.870	0.873	4.037	3.729	4.893
100	14.7231	2.7410	1.896	0.845	4.039	3.719	4.980
110	14.7315	2.7374	1.917	0.818	4.041	3.711	5.072
120	14.7399	2.7338	1.939	0.793	4.042	3.703	5.163
130	14.7483	2.7301	1.959	0.769	4.044	3.696	5.355
140	14.7565	2.7265	1.979	0.746	4.046	3.689	5.520

d+d → d+d: θ_d^{el} = 14.636 °, p_d =2.7757 GeV

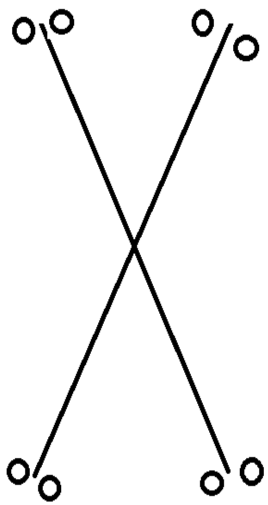
*) V.S.Kurbatov

The first and second stages of a possible experiment

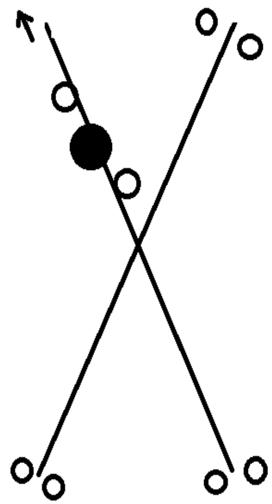
- At the **first stage**, which does not require a radical increase in measurement accuracy, one can verify the **very existence of the kinematic signature of dibaryons**.
- The **second stage** requires the improvement of the measurement accuracy of the proton momentum to 1%. If this can be done, then it will be possible to determine **whether the dibaryons are hot pieces of quark-gluon plasma, which have a temperature**, or **they are characterized by certain masses and widths**. If it turns out that the second possibility is realized, then a proton momentum measurement **accuracy of 1% would be sufficient to determine these characteristics**.

Why do we need a nucleon momentum generator at NICA SPD ?

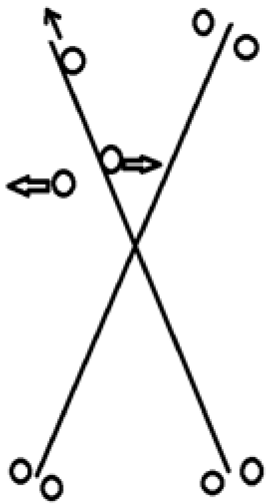
The kinematic signature can be forged!



Elastic d-d scattering

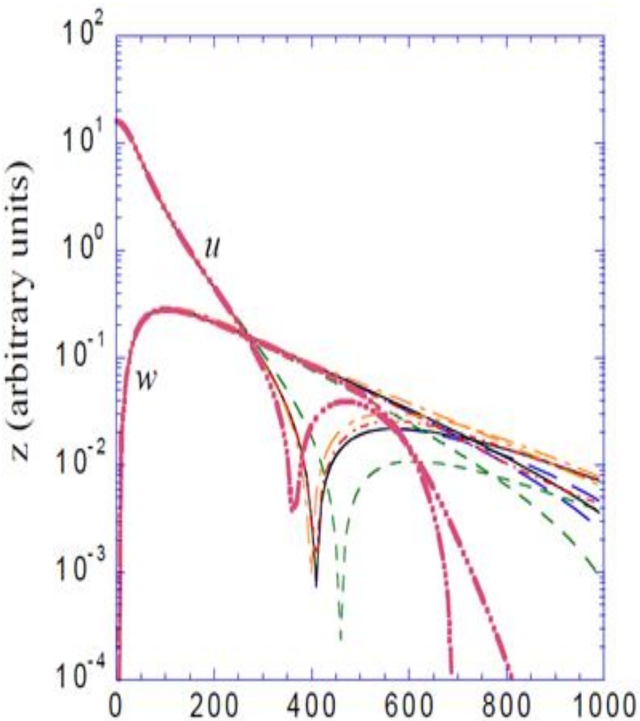


Kinematic signature of dibaryon decay: the proton flies into the region of elastic d-d scattering angles



Imitation (Fake): knocking out a high-momentum nucleon from deuteron by another colliding deuteron. The proton flies into the region of elastic d-d scattering angles, the scattered deuteron also flies approximately into this region

Challenges of Monte Carlo modeling



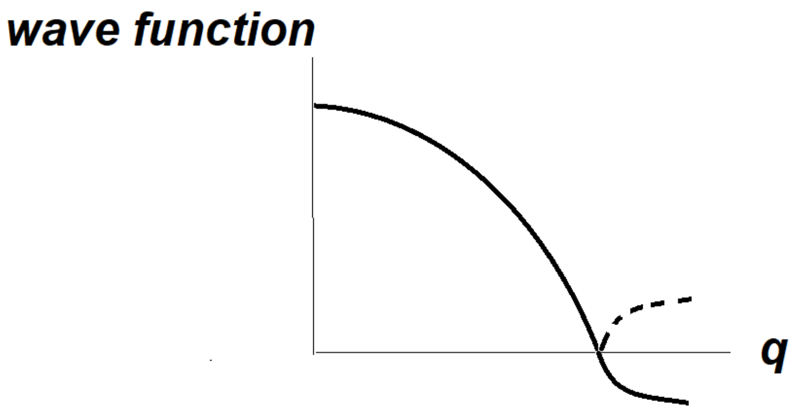
The u and w wavefunctions in p space for six models discussed in the text.

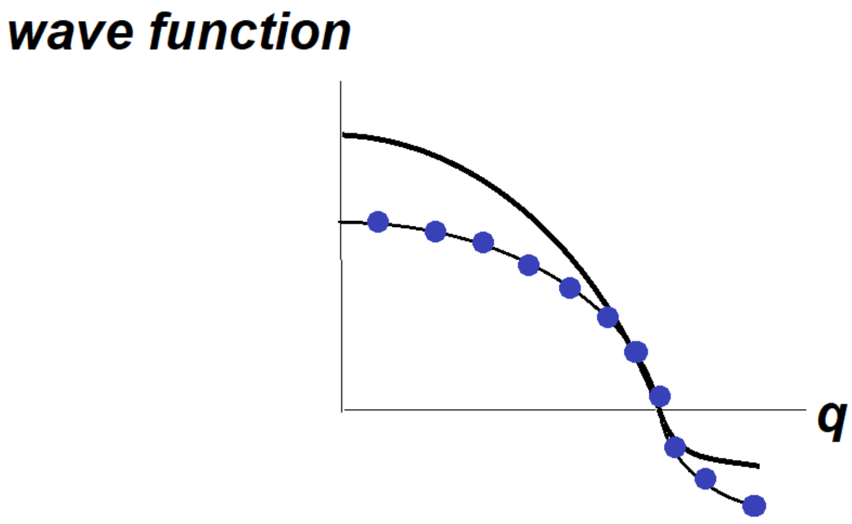
The von Neumann exclusion method is extremely ineffective here due to a **wide range of variation of probabilities** of admissible momentum values.

The **lack of an explicit analytical expression** for the cumulative distribution function seems to be an insurmountable obstacle to the use of another general approach - the method of inverse transformation of N. V. Smirnov.

Franz Gross, JLAB-THY-02-43

Nonlinear (smoothing) wave function transformation $\psi \rightarrow \phi$

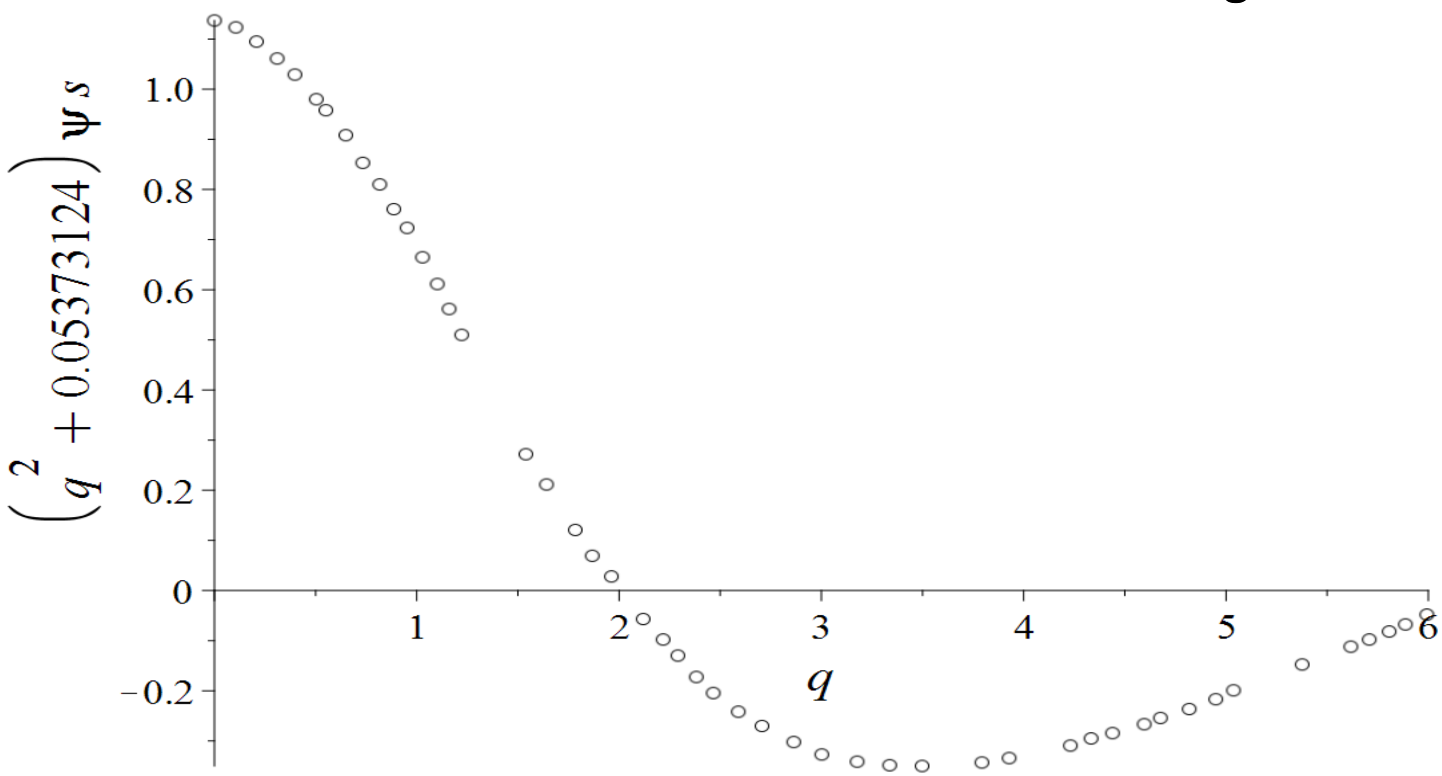




Getting rid of cusp by **reflection** into the region of negative values of the wave function.

Then we perform a nonlinear **smoothing** transformation and, after that, **split** (by eye) the curve into approximately linearly varying segments.

Deuteron's **transformed** wave function, $\boldsymbol{\phi=\psi\cdot(q^2+a^2)}$, for S-state after segmentation looks like this ($a=m_N\cdot E_{d\ binding}$)



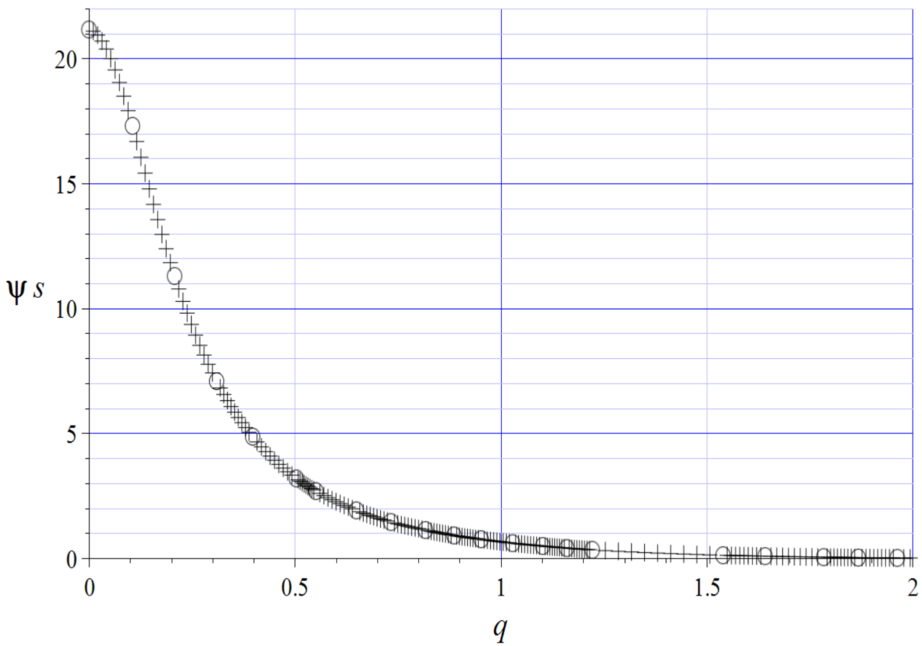
$[q]$=fm^{-1}

Linear interpolation in each partition interval:

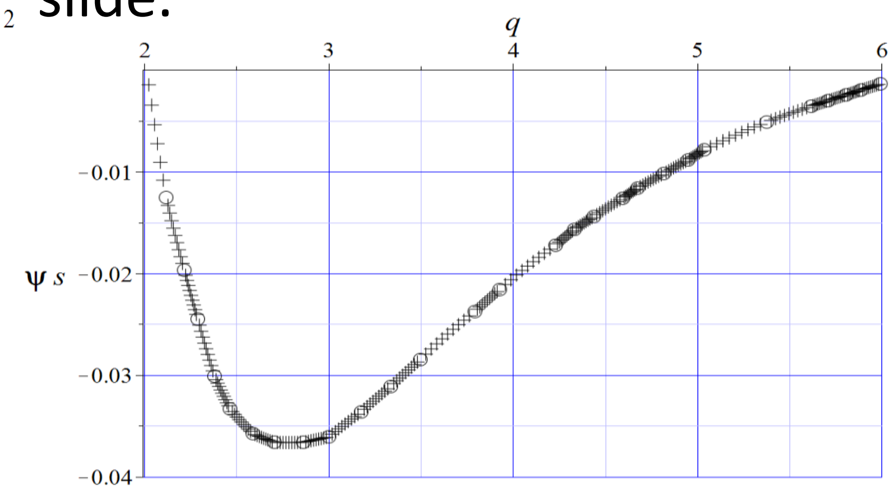
Tangent of the slope of a line segment

u (q[i]+x) = u (q[i]) + ki· x,
where 0 ≤ x ≤ q[i+1] - q[i],
ki = (u (q[i+1]) - u (q[i])) /(q[i+1] - q[i]).

Return to the **true** wave function ψ :
$\psi = \phi/(q^2+0.2318^2)$



The **circles show digitized values** of the wave function from Brown, Jackson. Nucleon-nucleon interactions. The crosses show the values of the wave function obtained by the **linear interpolation for ϕ** described on the previous slide.



It seems surprising that the same analytic formula (shown in the slide title) depicts very different behavior of the wave function between tabulated points (circles).

Cumulative probability function for the i-th interval

Interpolation for wave function ψ is in curly brackets

Geometric multiplier for integration in 3-D momentum space

$$\int_{qi}^{qi+x} \left\{ \frac{(ui + ki \cdot x)^2}{\left((qi+x)^2 + 0.2318^2\right)^2} \right\} \cdot (qi+x)^2 \, dx$$

The integral **can be computed analytically** and is cumbersome.

Obtained analytical expression, F(u, q,k,x), for the integral admits a numerical solution of the equation $\mathbf{q=F^{-1}(\xi)}$. Thus, the problem of drawing the values of the random variable q in accordance with its cumulative probability distribution may solved by the inverse transformation method.

Program of drawing random values of nucleon momentum according to the deuteron wave function is very short

$num := 1$; **for** i **from** 1 **to** 100000 **do** **if** $y[i] \le Scaled[num, 1]$ **then** $interval := 1$ **elif** $y[i] \le Scaled[num, 2]$ **then** $interval := 2$ **elif** $y[i] \le Scaled[num, 3]$ **then** $intreval := 3$ **elif** $y[i] \le Scaled[num, 4]$ **then** $interval := 4$ **elif** $y[i] \le Scaled[num, 5]$ **then** $interval := 5$ **elif** $y[i] \le Scaled[num, 6]$ **then** $interval := 6$ **elif** $y[i] \le Scaled[num, 7]$ **then** $interval := 7$ **elif** $y[i] \le Scaled[num, 8]$ **then** $interval := 8$ **elif** $y[i] \le Scaled[num, 9]$ **then** $interval := 9$ **elif** $y[i] \le Scaled[num, 10]$ **then** $interval := 10$ **elif** $y[i] \le Scaled[num, 11]$ **then** $interval := 11$ **elif** $y[i] \le Scaled[num, 12]$ **then** $interval := 12$ **end if**; $ind := 4\,interval - 3$; **for** j **from** 1 **to** 3 **while** $y[i] > PFi[num, ind]$ **do** $ind := ind + 1$ **od**; $q[i] := fsolve(PFi[1, ind] + F(ui[1, ind], qi[1, ind], ki[1, ind], X) - Fi[1, ind] = y[i], X)$ **end do**:

A personal computer (RAM 3.5 GB, processor with two cores at 3 GHz) calculates 100 000 random values of the nucleon momentum in the deuterium over the entire admissible range of its variations in only 16 minutes.

What to do in the near future?

1. Perform mathematical modeling of collisions of a deuteron in the collider beam with intranuclear nucleons inside another deuteron in the framework of the short-range correlation model (which assumes that high-momentum nucleons are present in the nucleus even before the collision). Estimate the possible contribution of these processes to the kinematic signature of dibaryons based on the experimental scheem shown in slide 17.

2. Develop a model and experimental scheme under the assumption that high-momentum nucleons appear in the deuteron only at the moment of the 6q splitting as a result of collision with another deuteron to evaluate the possibility of measuring small decrease in the momentum of such deuterons (already at the first stage of work at the NICA SPD facility, see presentation by V. S. Kurbatov at this Conference).

Appendix

Results of structure function ratio $R^d_{EMC} = \frac{F_2^d}{F_2^p+F_2^n}$ measurement were reported in [PRC 92 (2015) 015211]. Using it, one can estimate the coefficient n^d_{SRC} in (1)as follows. First, let us write

$$\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} = 1 - \frac{1}{R^d_{EMC}}, \tag{2}$$

where, according to [PRC 92 (2015) 015211], $R^d_{EMC} = 1 + C(x_B - 0.35)$, and $C \approx -0.10$ for $0.35 \leq x_B \leq 0.70$. One finds from Fig. 2b in [Nature, 566(2019)354] for $x_B = 0.5$

$$n^d_{SRC}\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} = -0.015 \pm 0.007,$$

where -0.015 is the arithmetical mean of maximal and minimal values in the graph at $x_B = 0.5$. The value of 0.007 displays uncertainties of the right side of (1) due to its residual dependence on nuclei. On the other hand, it is easy to check that left side of equation (2) is equal to -0.015 too at $x_b = 0.5$. It immediately follows from this that $n^d_{SRC} = 1$. Similarly, for $x_B = 0.7$, where right side of equation (1) is equal to -0.033 ± 0.007, left side of (2) is equal to -0.036. This value is also consistent with the statement that $n^d_{SRC} = 1$ within the accuracy of the model.

Thank you for your attention!