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A.A. Kasparov, M.V. Mordovskoy, A.A. Afonin,
S.I. Potashev, V.V. Mitcuk

(Institute for Nuclear Research, Russian Academy of Sciences)

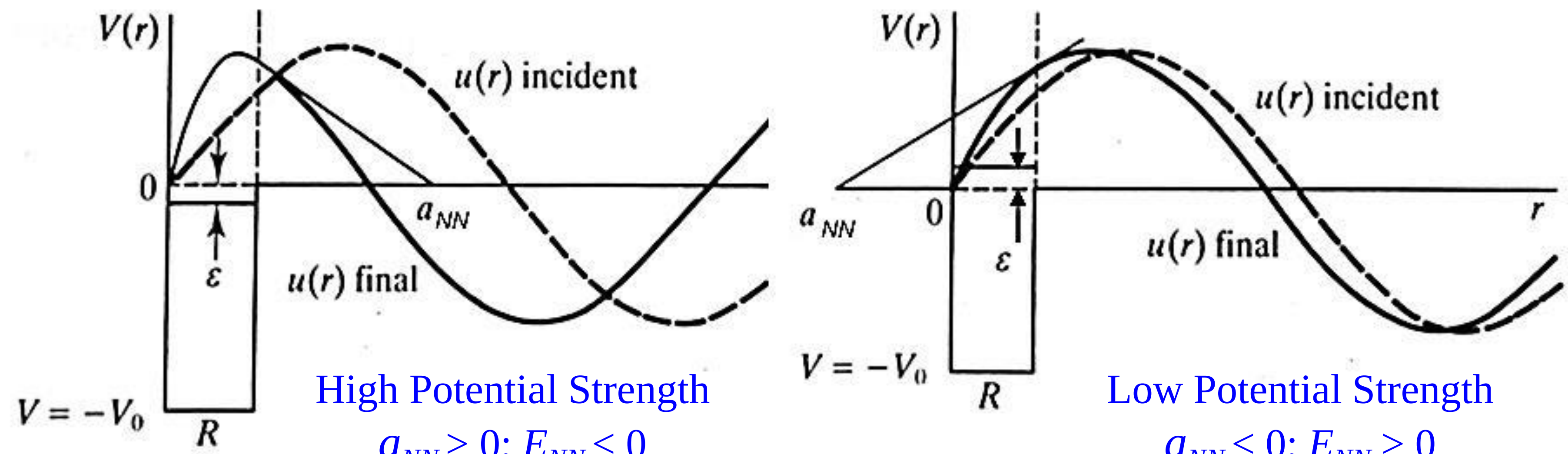
DATA ON THE *np*-SCATTERING LENGTH FROM THE *nd*-BREAKUP REACTION AT LOW ENERGIES

INR RAS 2022

Low-Energy Parameters of NN-Interaction

NN-Scattering Lengths a_{NN} and NN-Virtual State Energy E_{NN}

$$\frac{1}{a_{NN}} = -\left(\frac{m_N E_{NN}}{\hbar^2}\right)^{1/2} - \frac{1}{2} r_{NN} \frac{m_N E_{NN}}{\hbar^2} + \ldots$$



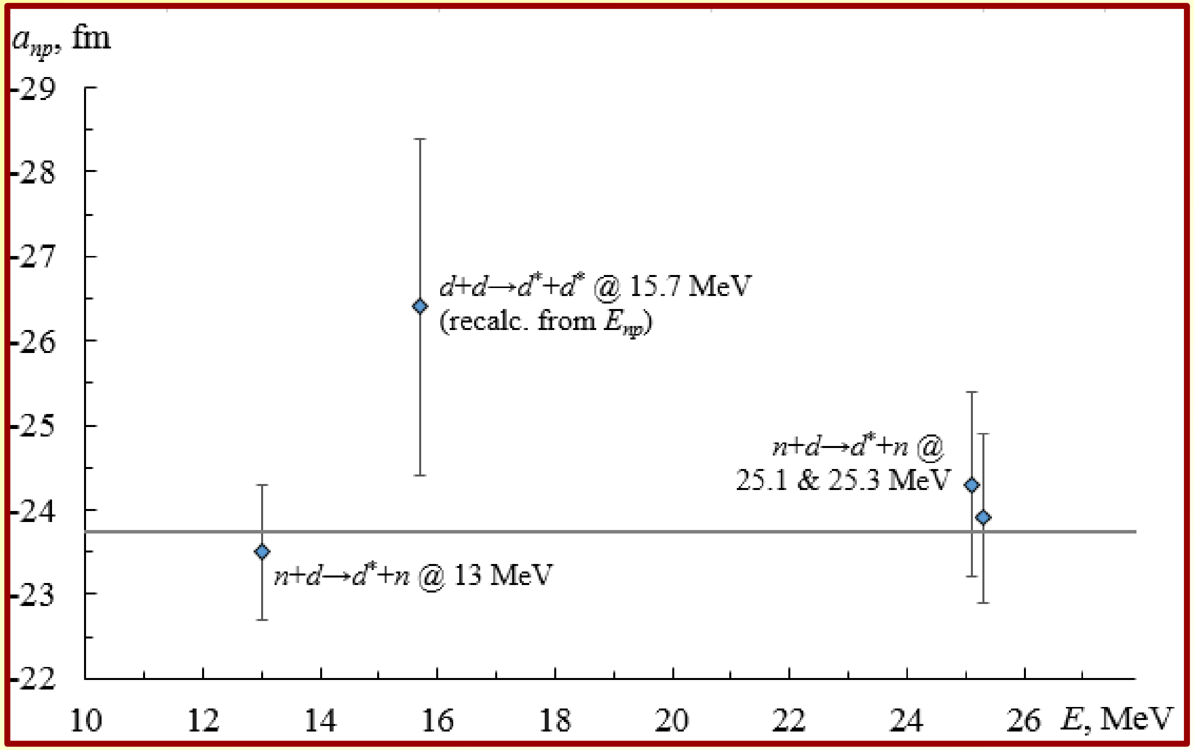
High Potential Strength
$a_{NN} > 0;\ E_{NN} < 0$

Low Potential Strength
$a_{NN} < 0;\ E_{NN} > 0$

Scattering length is determined as the intersection point of the tangent at the joining point of the inner and outer WF with the R-axis.

Small change in potential strength can lead to a significant change in the scattering length.

Data on Neutron-Proton Scattering Length



Accurate experimental data on the scattering lengths and their differences may provide a quantitative estimate of the charge symmetry breaking (CSB) and charge independence breaking (CIB) of nuclear forces

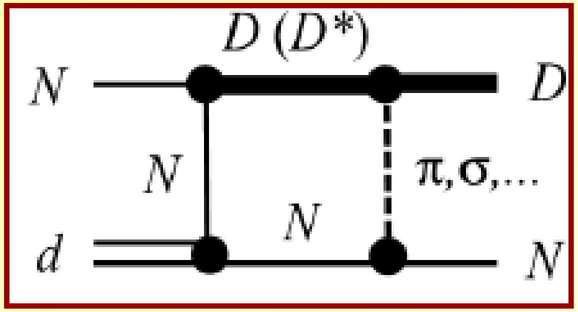
a_{np}= -23.748±0.010 fm is determined from direct measurement of the *np*-scattering (grey line)

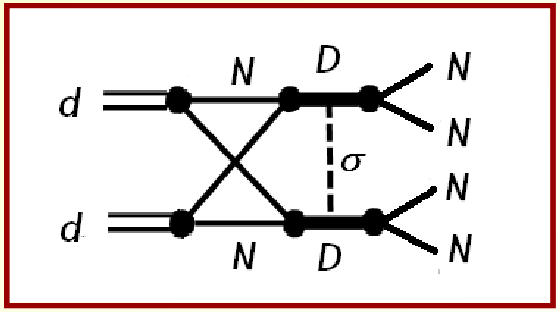
Dibaryon Model (V.I. Kukulin *et al.*)

New mechanism arising in the Dibaryon Model: New force – meson exchange between the nucleon and dibaryon

$nd \rightarrow np + n$

$dd \rightarrow \mathrm{D} + \mathrm{D} \rightarrow n + n + p + p$





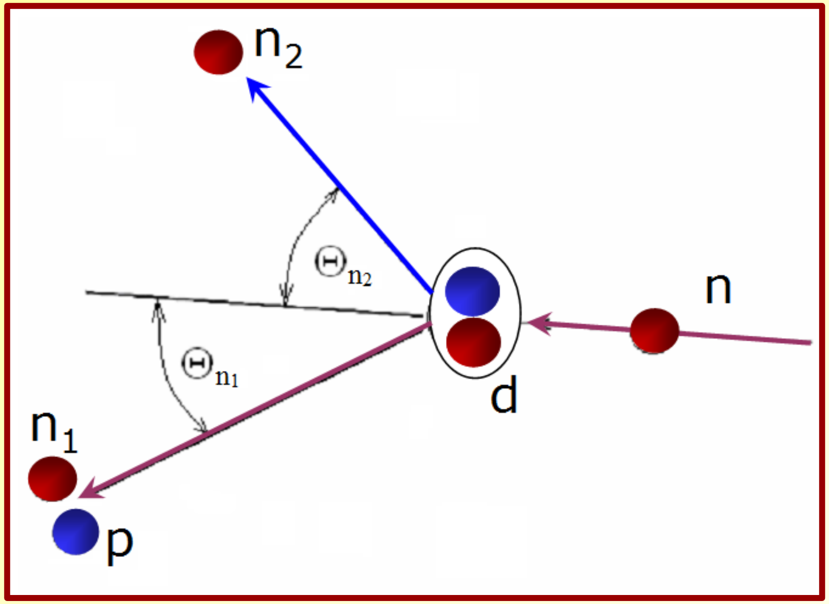
Such additional interaction can lead to a change in the values of a_{np} and E_{np}. The degree of this change may depend on the relative velocity of the fragments - *np*-pair and *n* or *np*-pair and diproton for *nd*- and *dd*-breakup, respectively.

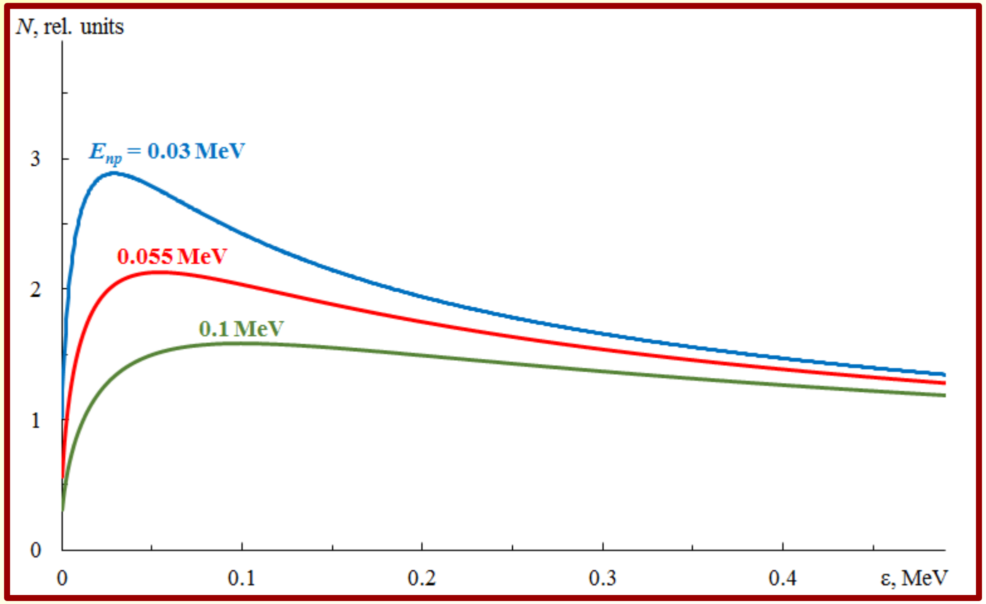
Study of neutron–proton final state interaction (FSI) in $n + d \rightarrow p + n + n$ reaction (*recoil* geometry)

Registration of two neutrons, neutron and proton have a very small relative momentum

Watson-Migdal approximation

$$\frac{dN}{d\varepsilon}_{WM} = \frac{\sqrt{\varepsilon}}{\varepsilon + E_{np}}$$





Neutron–proton FSI manifests itself as a peak in the dependence of the reaction yield on the relative energy of two neutrons $\varepsilon = \frac{1}{2} \cdot \left(E_1 + E_2 - 2 \cdot \sqrt{E_1 \cdot E_2} \cdot \cos \Delta\Theta \right)$

The shape of this dependence $N(\varepsilon)$ is sensitive to E_{np} and a_{np}, accordingly.

Simulation of *nd*-Breakup Yield vs ε @ 8–13 MeV

First stage

$n + {}^2\mathrm{H} \rightarrow np + n$

$M_{np} = m_n + m_p + \varepsilon$

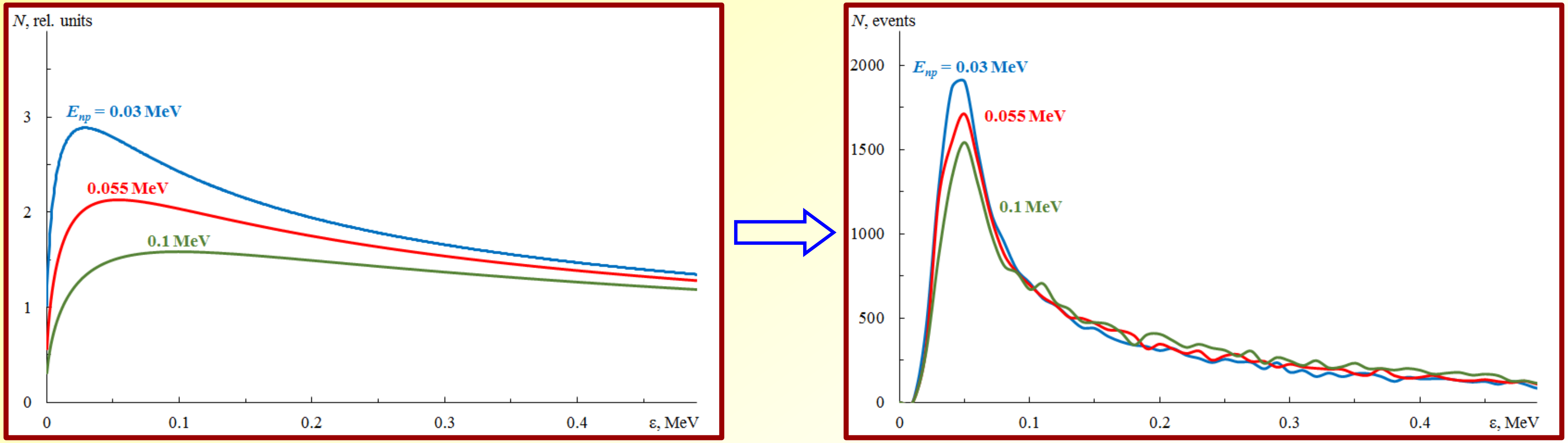
$N(\varepsilon)$ – MW

Second stage

$np \rightarrow n + p$

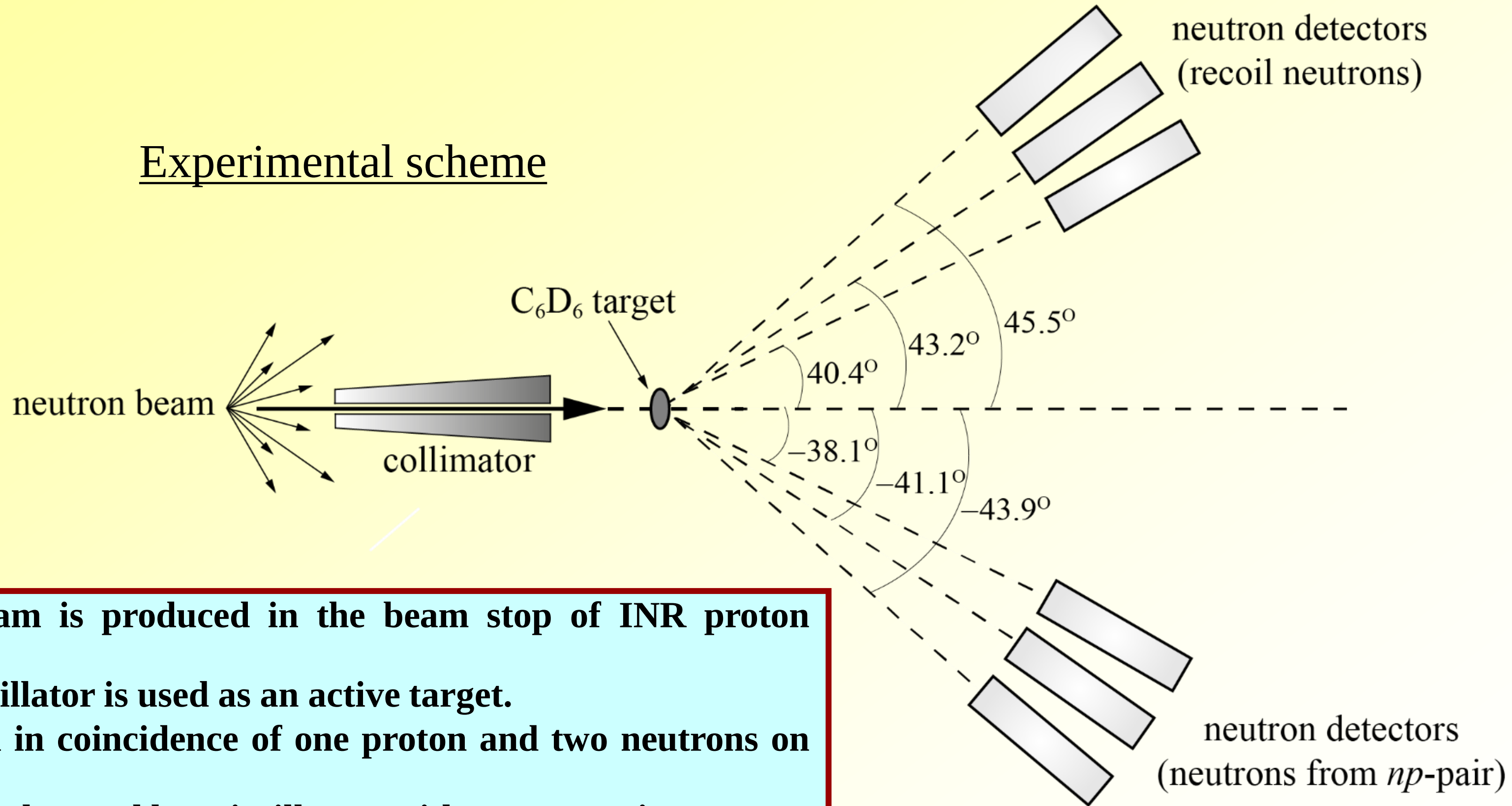
Experimental conditions

$N(\varepsilon) = f\,(E_{np})$



Simulated distribution of the reaction yield on the relative energy depends on E_{np} (a_{np})

Determination of E_{np} and a_{np} in $n + {}^2H \rightarrow n + n + p$ reaction at $E_n = 8 – 13$ MeV



- **Neutron beam is produced in the beam stop of INR proton accelerator**
- **A C_6D_6 scintillator is used as an active target.**
- **Registration in coincidence of one proton and two neutrons on opposite sides**
- **Neutrons are detected by scintillators with *nγ*-separation**
- **Energy and angle of the proton are recovered from the conservation laws**
- **The dependence of *nd*-breakup yield on *np*-relative energy were compared with MW calculation depending on E_{np} value**

Experiment vs Simulation.

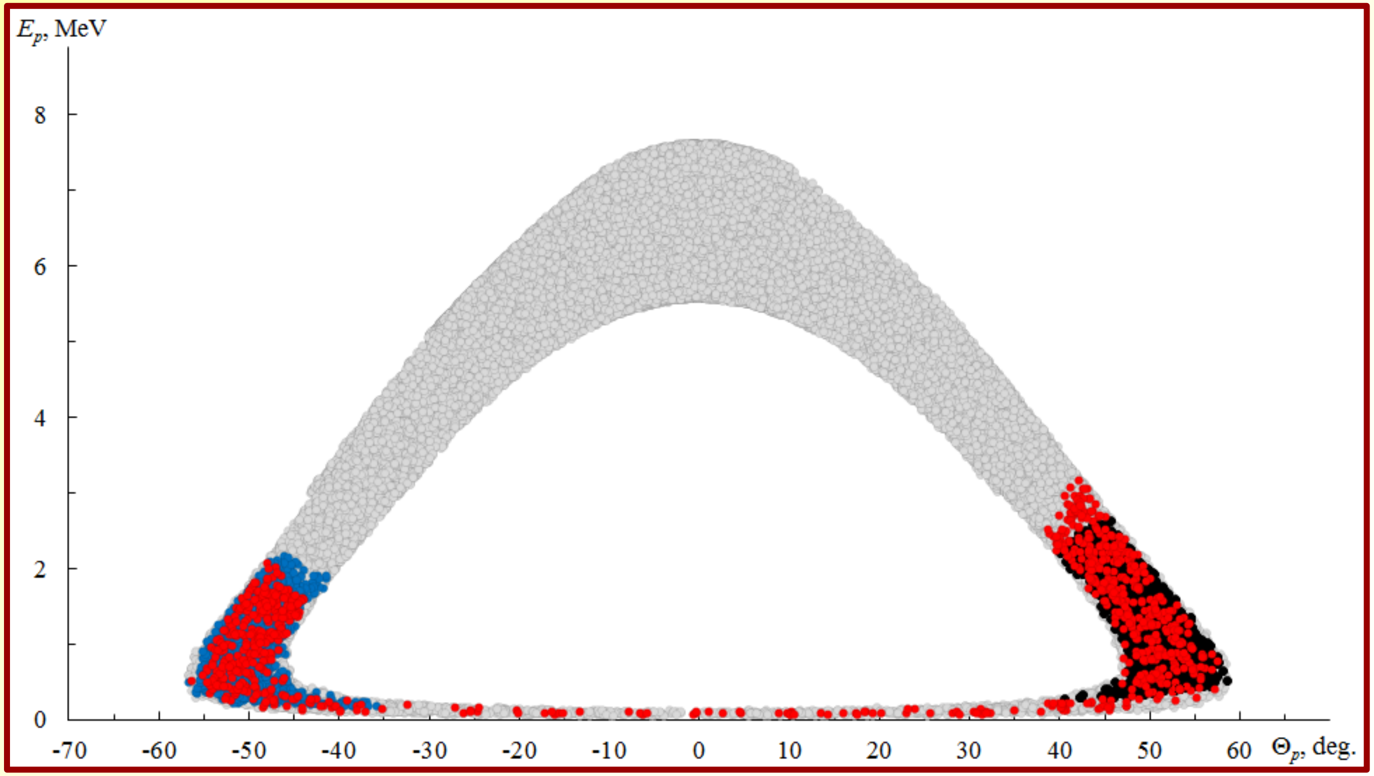
$E_0 = 9 \pm 1$ MeV; $\Theta_{n1} = -38.07^{O} \pm 0.83^{O}$; $\Theta_{n2} = 45.47^{O} \pm 0.78^{O}$

Grey area – simulation $n + {}^2H \rightarrow n_1 + p + n_2$ reaction (democratic breakup);

Black area – simulation $n + {}^2H \rightarrow (n_1p) + n_2 \rightarrow n_1 + p + n_2$ reaction (intermediate state);

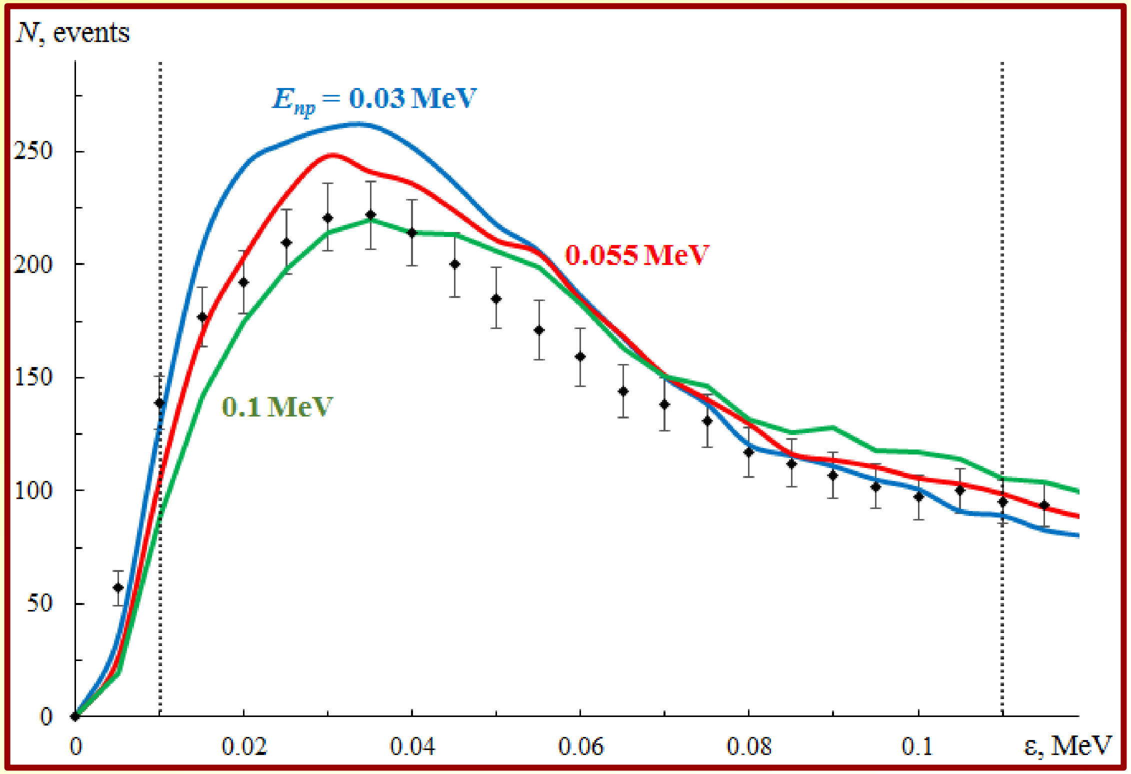
Blue area – simulation $n + {}^2H \rightarrow (n_2p) + n_1 \rightarrow n_2 + p + n_1$ reaction (intermediate state);

Red area – experiment



Experiment vs Simulation.
$E_0 = 9 \pm 1$ MeV

Total experimental dependence of the yield is compared with the simulation results for three values of np virtual energy 30, 55, and 100 keV.



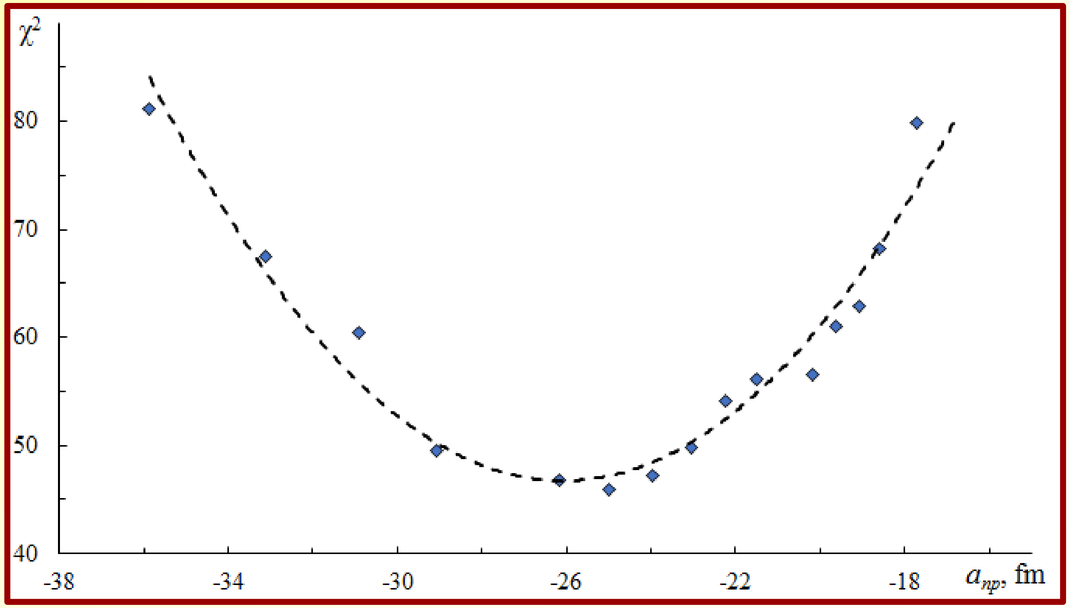
The best fit is obtained for E_{np} = 56 ± 5 keV

Determination of E_{np} from χ^2 versus a_{np} curve for $E_0 = 9 \pm 1$ MeV and $E_0 = 11 \pm 1$ MeV

Comparing experimental yield with simulation results for different a_{np}

$$\chi^2(a_{np}) = \sum_{\varepsilon} \frac{\left(\frac{dN^{\exp}(\Delta\Theta)}{d\varepsilon} - A\frac{dN^{\text{sim}}(\Delta\Theta)}{d\varepsilon} \right)^2}{\left(\Delta\frac{dN^{\exp}(\Delta\Theta)}{d\varepsilon} \right)^2}$$

Summed over 21 points ε = 0.01 – 0.11



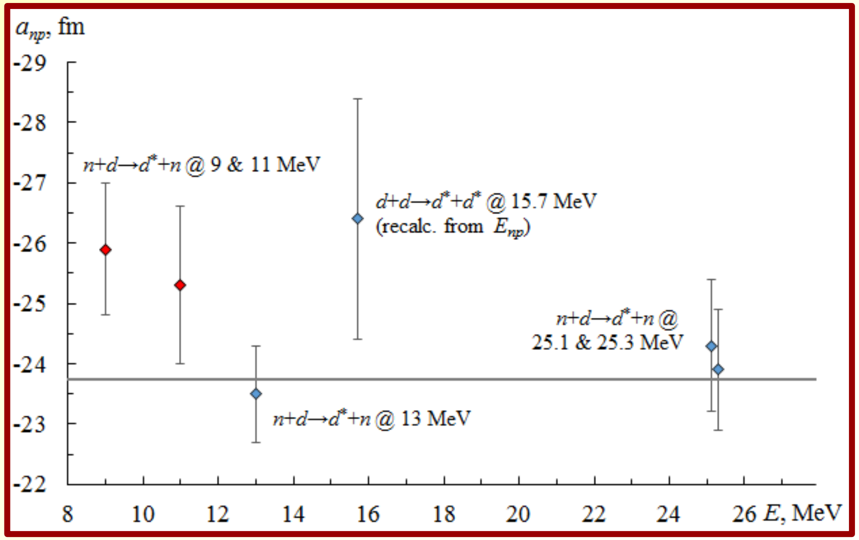
$$\frac{1}{a_{NN}} = -\left(\frac{m_N E_{NN}}{\hbar^2} \right)^{1/2} - \frac{1}{2} r_{NN} \frac{m_N E_{NN}}{\hbar^2} + \ldots$$

$r_{np} = 2.76$ fm

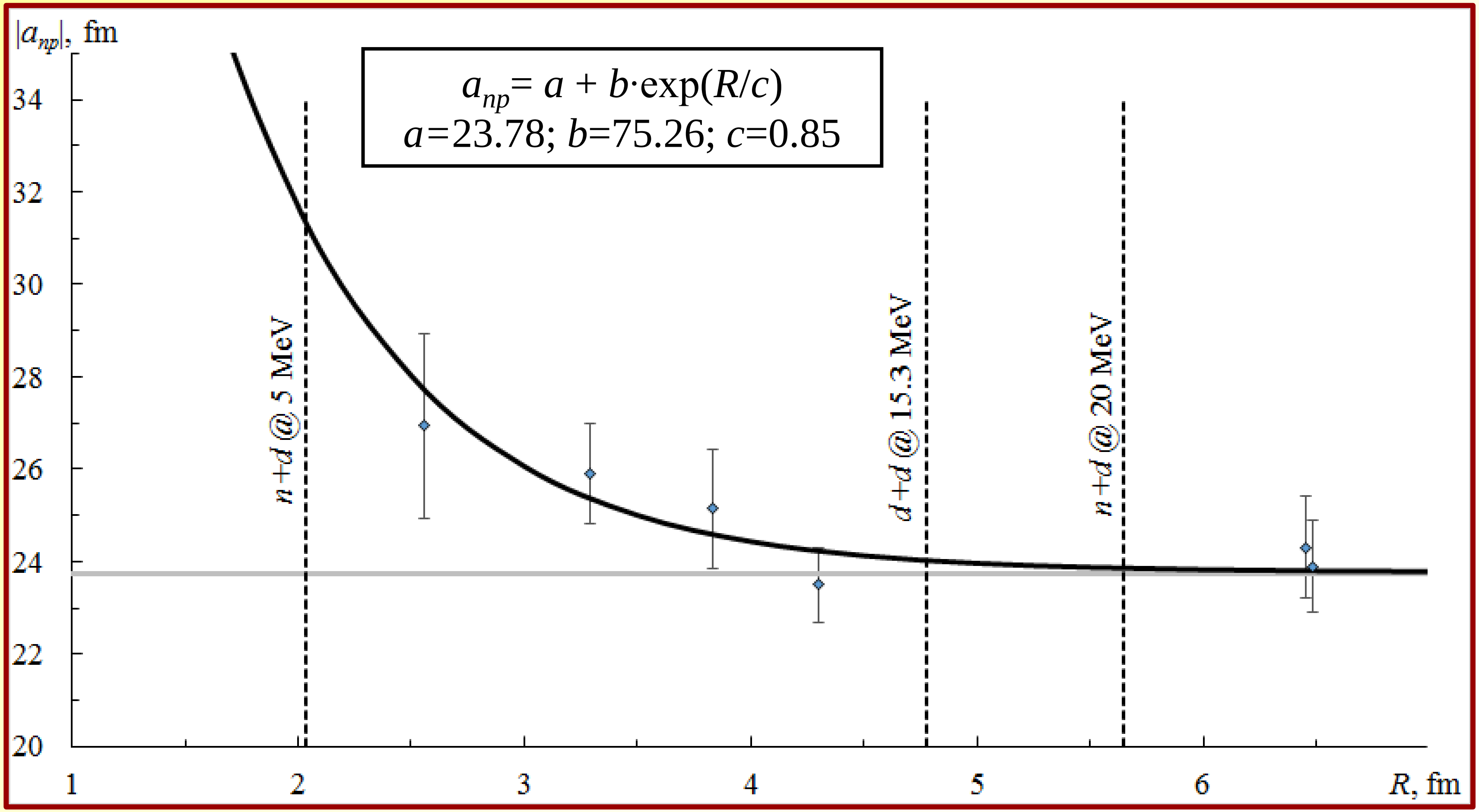
Output data at 9 MeV
$a_{np} = -25.9 \pm 1.1$ fm (Recalc. from E_{np})
Output data at 11 MeV
$a_{np} = -25.1 \pm 1.3$ fm (Recalc. from E_{np})

Conclusions

- **A kinematically complete *nd*-breakup experiment at neutron energies 9 and 11 MeV was performed at neutron channel RADEX of INR RAS.**
- **The shape analysis of the dependence of reaction yield on *np* relative energy allows to determine Low Energy Parameters of *np*-interaction: $a_{nn} = -25.9 \pm 1.1$ fm and $a_{np} = -25.1 \pm 1.2$ fm at 9 and 11 MeV, respectively.**
- **The obtained value of the *np*-scattering length differs significantlyfrom the value obtained in direct *np*-scattering and, in our opinion, indicates an effective enhancement of the *np*-interaction in the presence of a third nucleon (can be associated with a significant influence of 3*N*-forces).**



Thank you!


$|a_{np}|$, fm
$a_{np} = a + b \cdot \exp(R/c)$
a=23.78; b=75.26; c=0.85
$n+d$ @ 5 MeV
$d+d$ @ 15.3 MeV
$n+d$ @ 20 MeV
34
32
30
28
26
24
22
20
1
2
3
4
5
6
R, fm