INTERNATIONAL SESSION-CONFERENCE
"Physics of fundamental interactions“
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Study of Charge Symmetry Breaking Effect in *dd*- and *Nd*-Breakup Reactions

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Charge Symmetry Breaking in *NN*-Interaction

Soon after discovery of the neutron, V. Heisenberg in 1932 formulated the principle of charge independence (CI) of nuclear forces, according to which the interaction between any pair of nucleons (*pp, np, nn*) is the same.

$$F_{pp} = F_{np} = F_{nn}$$

Less weaker statement - the principle of charge symmetry (CS) states that *pp* and *nn* forces in the singlet state are equal.

$$F^S_{pp} = F^S_{nn} \text{ in } {}^1S_0 \text{ state } (T=1,\ S=0)$$

Charge symmetry breaking (CSB) is a small effect, which, according to the modern concepts, is related to the mass difference between ***up*** and ***down*** quarks and electromagnetic energy differences caused by their different electric charges and magnetic moments.

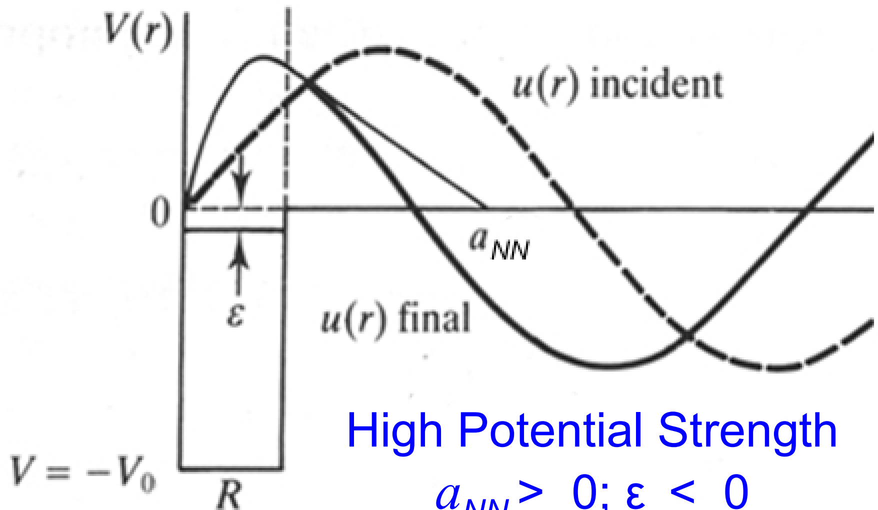
Due to presence of a virtual level with a close to zero energy in the singlet ${}^1S_0$ state of two nucleons, the NN scattering lengths (and energies of a virtual levels) are very sensitive to small changes in the *NN* potential

Low-Energy Parameters of *NN*-Interaction

NN Scattering Lengths a_{NN} and *NN* Virtual State Energy ε

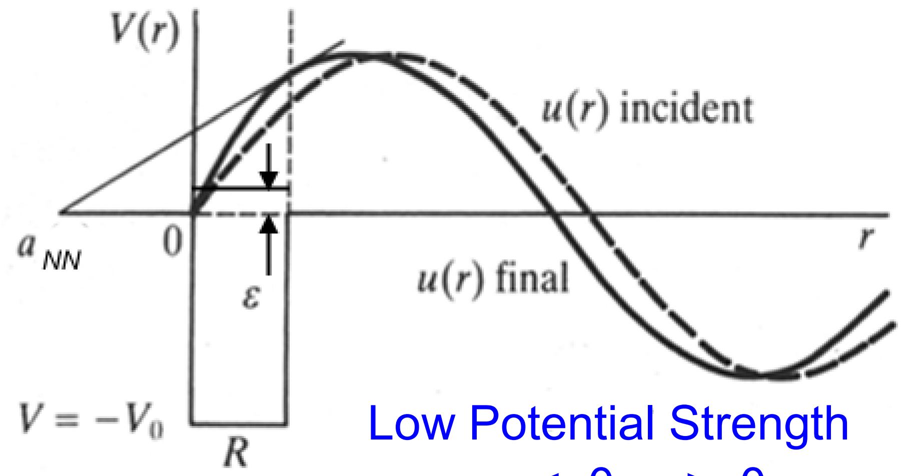
$$\sigma_0 = 4\pi a^2\left[\left(1-\tfrac{1}{2}aRk^2\right)^2 + a^2k^2\right]^{-1}$$

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



High Potential Strength

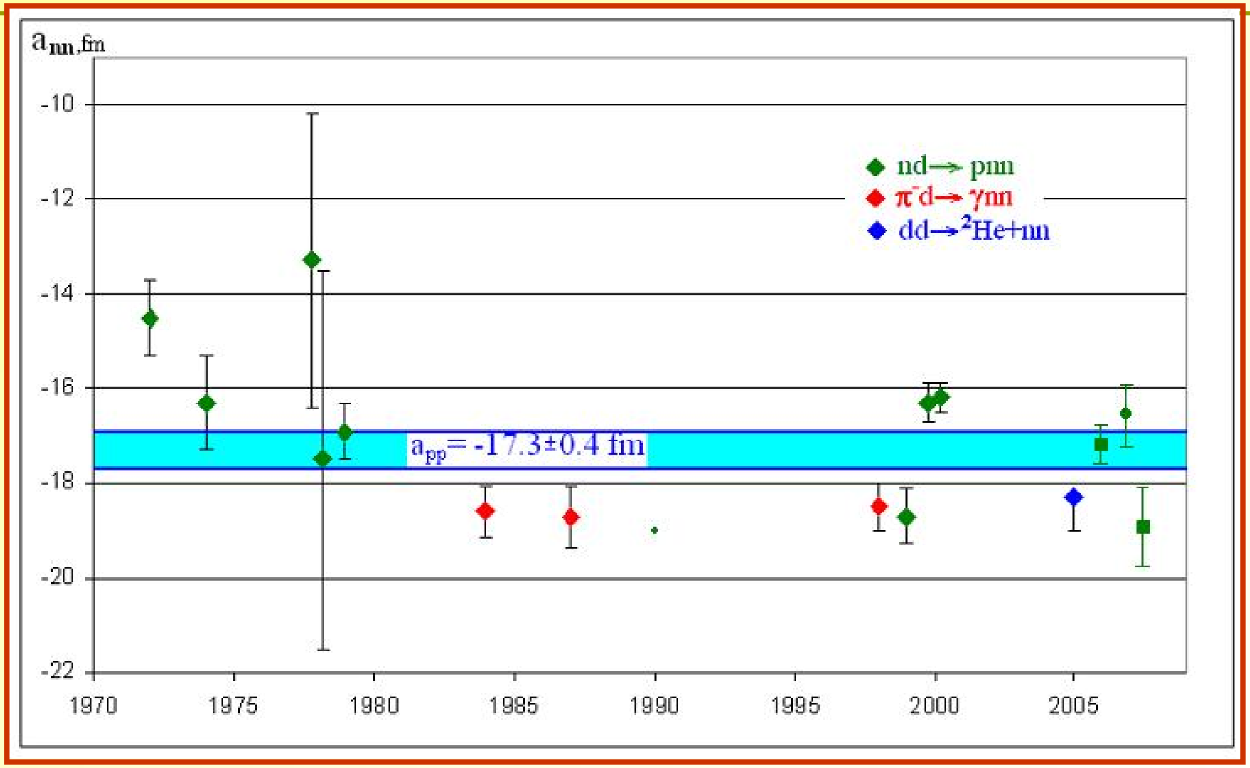
$a_{NN} > 0$; $\varepsilon < 0$



Low Potential Strength

$a_{NN} < 0$; $\varepsilon > 0$

Data on Proton-Proton and Neutron-Neutron Scattering Lengths

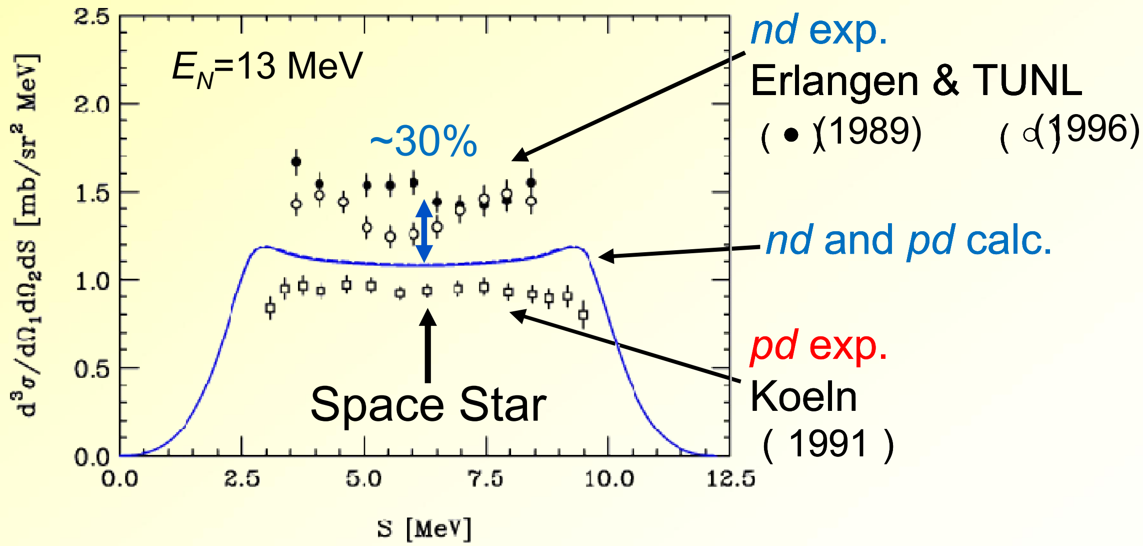


Neutron - neutron scattering length is determined using mostly ***n+d→p+n+n*** **and** ***π⁻+d→ γ+n+n*** reactions and investigating the region of the *n-n* FSI where two neutrons fly together with small relative energy

The results obtained by now testify significant uncertainty of a_{nn} values which are clustered near **-16.3±0.4** (Bonn) and **-18.5±0.4 fm** (TUNL, LAMPF), so there is even uncertainty about the sign of the difference a_{nn}-a_{pp} which is a measure of CSB

Space Star (SS) Anomaly in *pd* and *nd* breakup

A.Deltuva et al., PRC72,054004 (2005)
J.STRATE *et al.*, Nucl. Phys. A**501** (1989) 51
H.R.Setze *et al.*, Physics Letters B**388** (1996) 229
G.RAUPRICH *et al.*, Nucl. Phys. A**535** (1991) 313



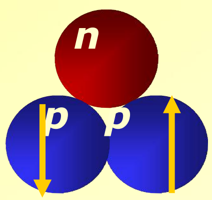
- At *pd* SS, exp. cross section is smaller than *pd* calc.
- At *nd* SS, exp. cross section is larger than *nd* calc.

^{3}He(ppn) and ^{3}H(nnp) Systems

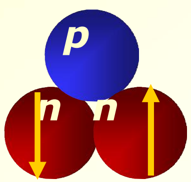
Two protons in ^{3}He are mainly in opposite spin states

Two neutrons in ^{3}H are also in a spin-singlet state

^{3}He



^{3}H



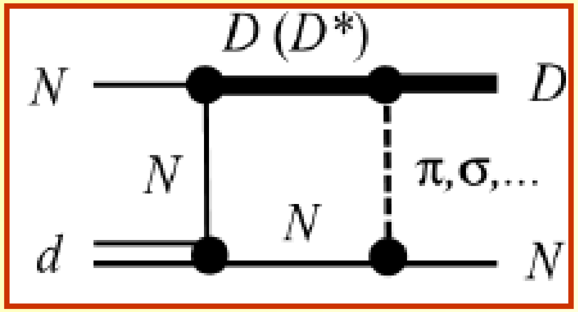
Strong discrepancies observed in Nd-breakup can be explained by a significant strengthening of *nn*- and *pp*-correlations of attractive character in the third nucleon field.

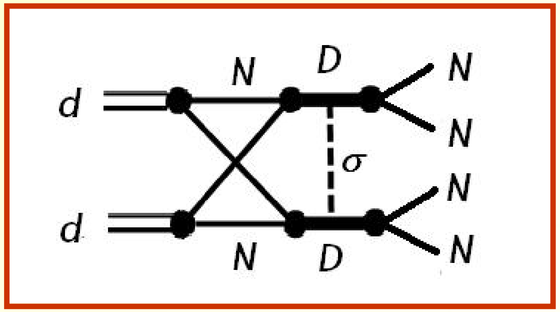
Dibaryon Model (Kukulin et al)

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

N*d* or *t* (^{3}He)

$dd \to$ D + D $\to n+n+p+p$

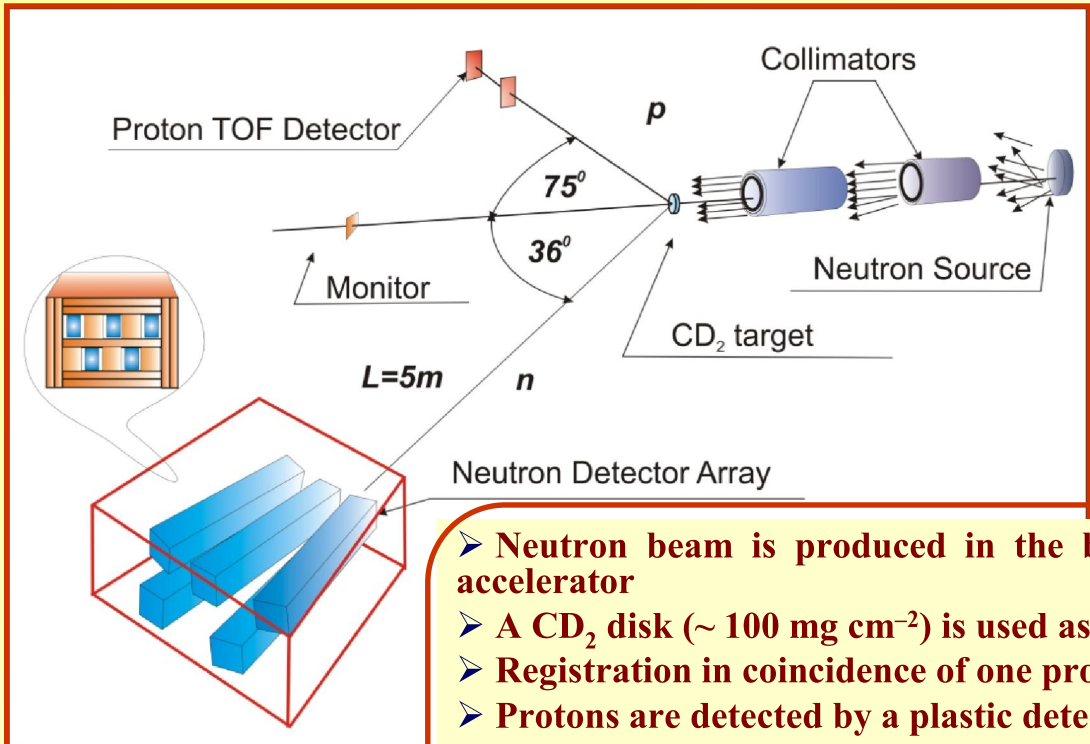




Our plans: study of *nd→p+nn*, *nt →d+nn* and *dd→pp+nn and* ….

In these reactions *nn*-correlated pair can be produced dynamically in the intermediate state. Thus, measured *nn*-correlation, in particular energy of *nn* virtual singlet state, may be different from those inherent for the free NN-systems.

Determination of *nn*-Virtual-State Energy and Scattering Length in $n + {}^2\mathrm{H} \rightarrow n + n + p$ Reaction @ 40 MeV



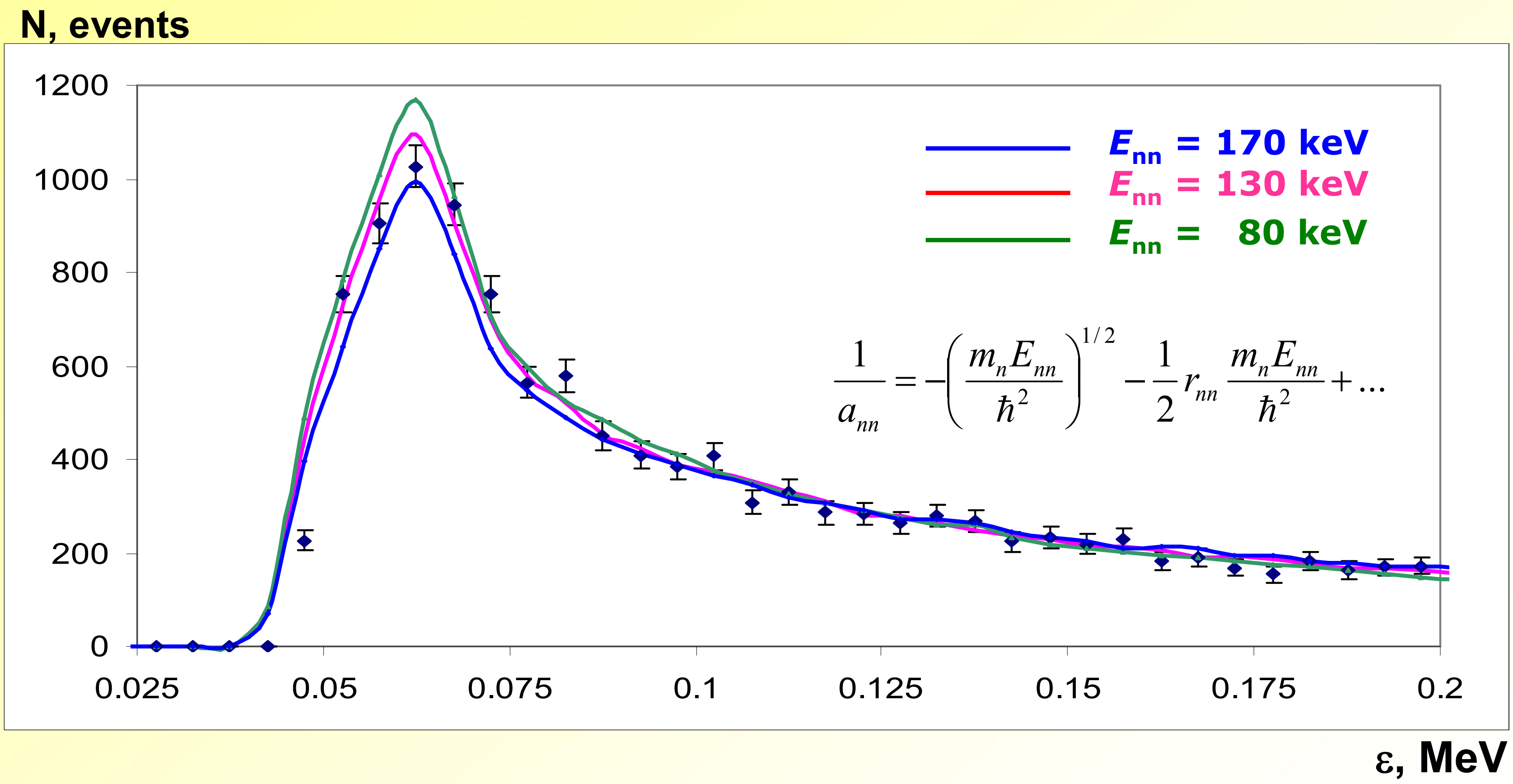
FSI

$\varepsilon = (E_{n1} + E_{n2} - 2(E_{n1}E_{n2})^{1/2}\cos\Delta\Theta)/2$

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

- **Neutron beam is produced in the beam stop of INR proton accelerator**
- **A CD_2 disk (~ 100 mg cm^{-2}) is used as the scattering target.**
- **Registration in coincidence of one proton and two neutrons**
- **Protons are detected by a plastic detector located at 75°±6°**
- **Neutrons are detected by a six-detector hodoscope at 30°-42°**
- **Energies of secondary neutrons are determined by a TOF technique**
- **Incident neutron energy and Θ_p are reconstructed from kinematics**

Experimental and simulated dependences N(ε) for various values of E_{nn} ; ΔΘ= 6°, E_0 = 40 ± 5 MeV

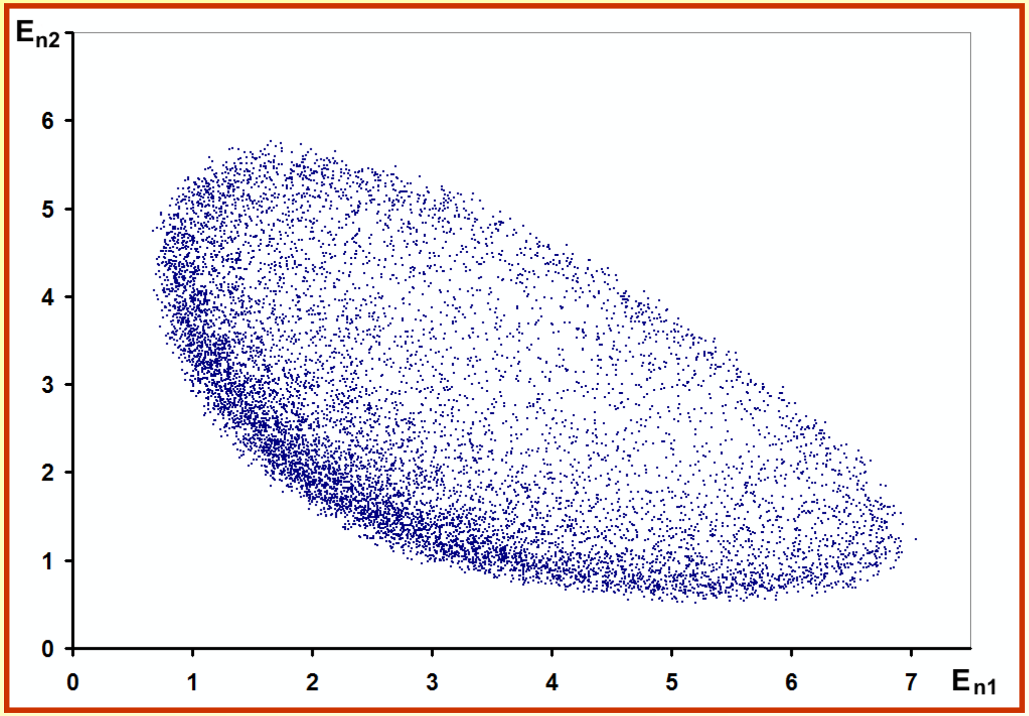


The best fit is obtained for E_{nn} = 129 ± 14 keV → a_{nn} = -16.6 ± 0.9 fm.

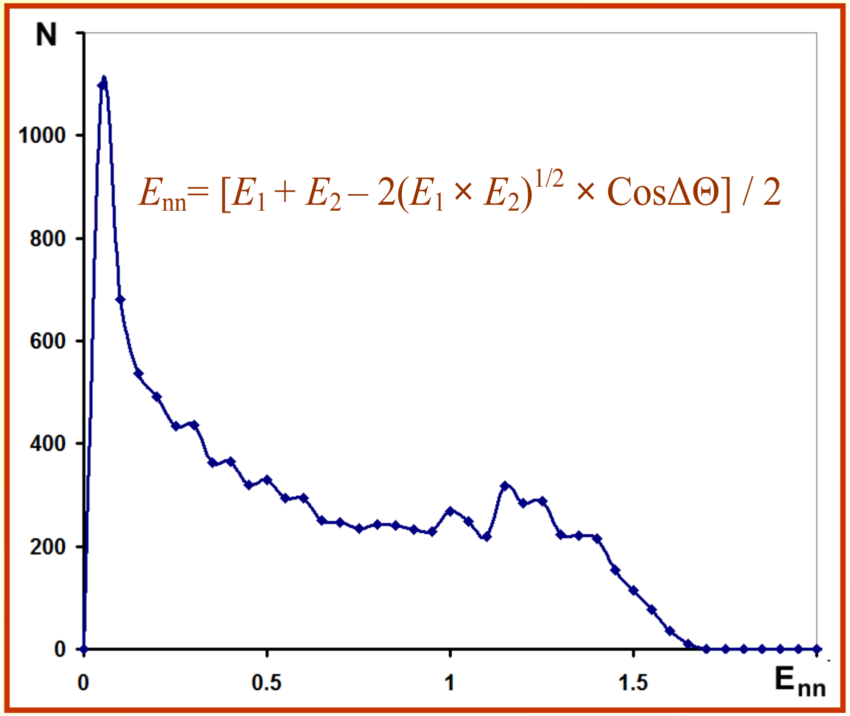
Determination of *nn*-Virtual-State Energy and Scattering Length in $d + {}^2\mathrm{H} \rightarrow (nn)^S + (pp)^S \rightarrow n+n+p+p$ Reaction

Simulation of $d + {}^2H \rightarrow n + n + p + p$ Reaction: $E_d = 15$ MeV, $\Theta_{p1} = 27^o$, $\Theta_{p2} = 27^o$, $\Theta_{n1} = 36^o$

E_{n1} vs E_{n2}



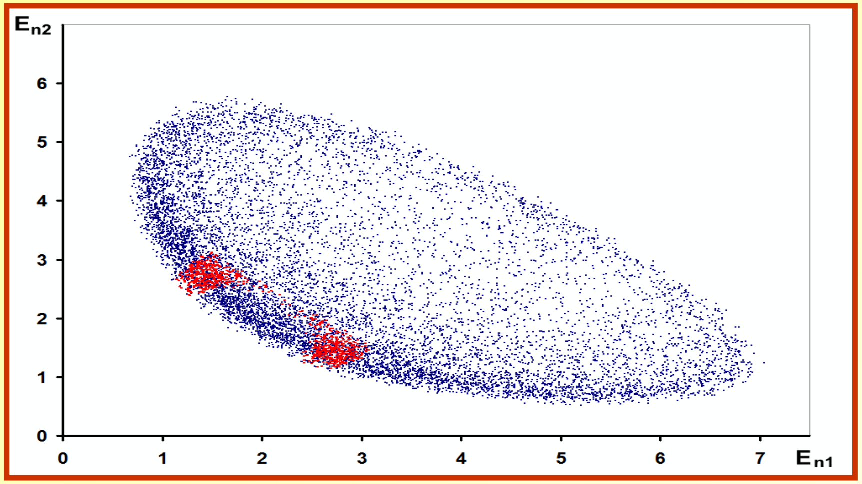
E_{nn} Spectrum



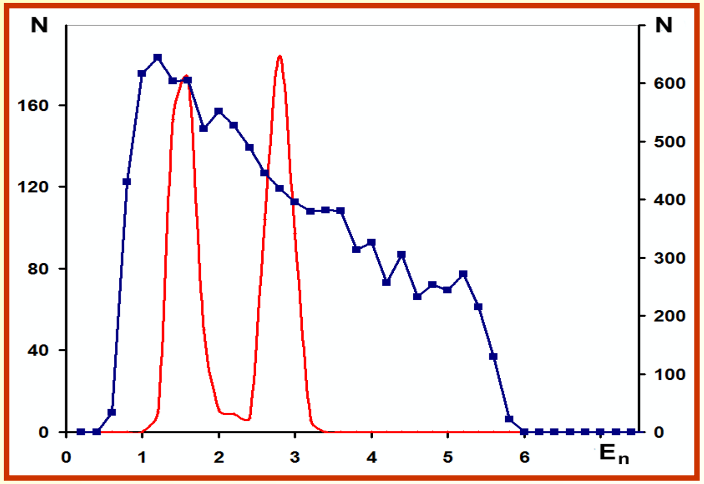
For democratic breakup two neutrons can have a relative energy in the range 0 - 1.8 MeV

Simulation of $d + {}^2\mathrm{H} \rightarrow n + n + p + p$ Reaction
Democratic breakup Vs Events with Selected Values of Enn

E_{n1} vs E_{n2}



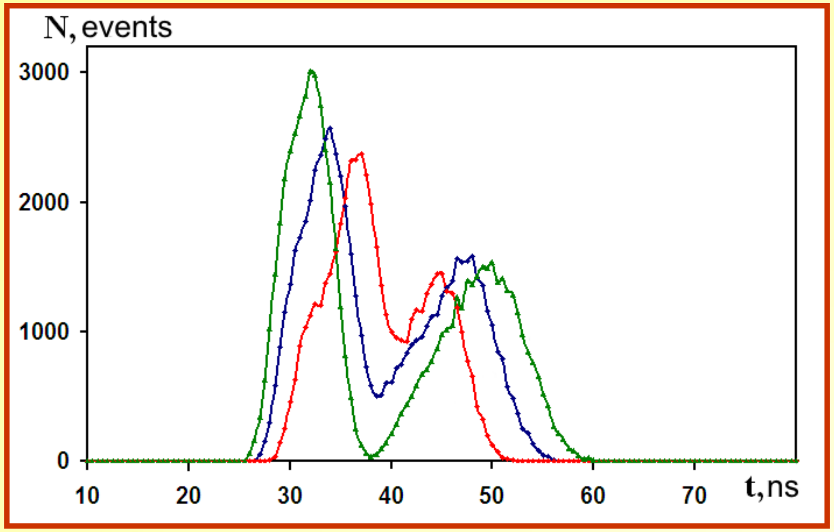
E_n Spectrum



Democratic Breakup and Selection E_{nn} = 120 keV, Γ_{nn} = 50 keV

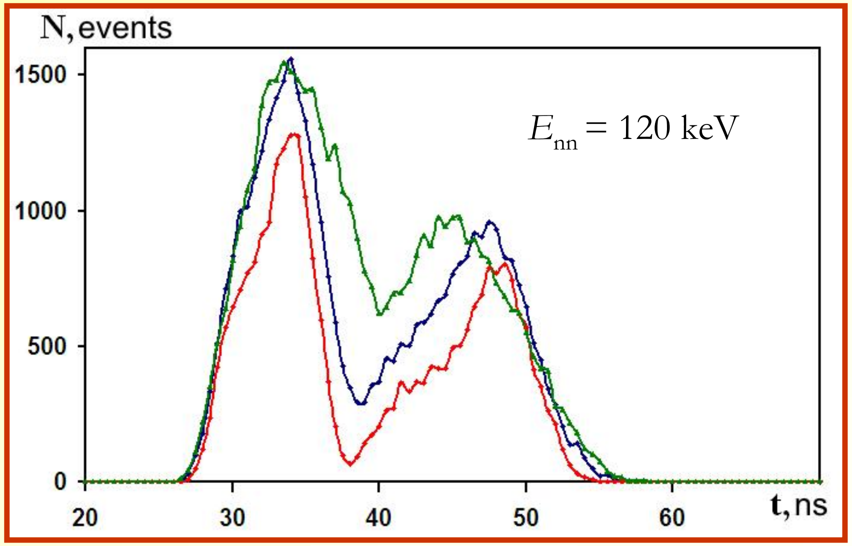
This structure in spectrum is due to the fact that to reach detector, installed at angle of emitting *nn*-system in two-body reaction, may only breakup particles emitted in c.m. system in forward or in backward direction

Simulation of $d + {}^2H \rightarrow n + n + p + p$ Reaction: Different Energies and Widths of the Singlet State



E_{nn} = 50 keV, Γ_{nn} = 30 keV
E_{nn} = 200 keV, Γ_{nn} = 100 keV
E_{nn} = 120 keV, Γ_{nn} = 70 keV

The distance between peaks depends on the excitation energy (excess mass of two-nucleon system over the sum of masses of its constituents)

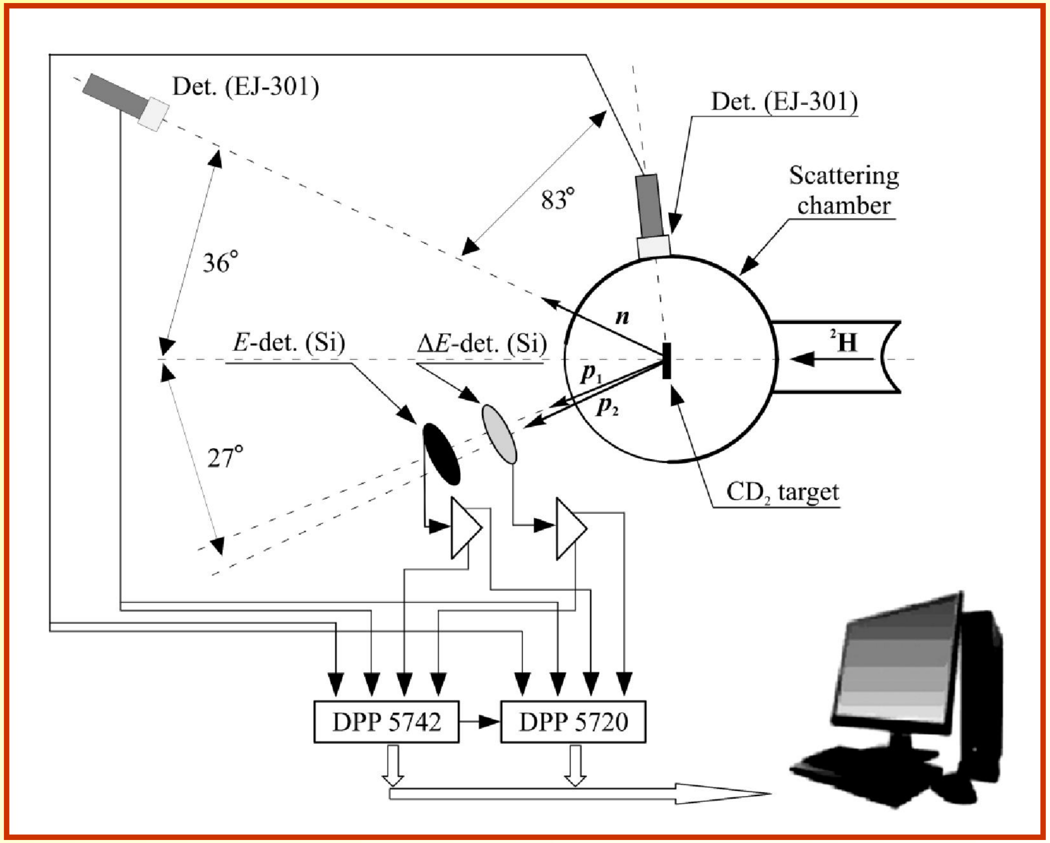


Γ_{nn} = 110 keV
Γ_{nn} = 70 keV
Γ_{nn} = 20 keV

The change of the state width affects mainly on degradation of "valley" between the peaks

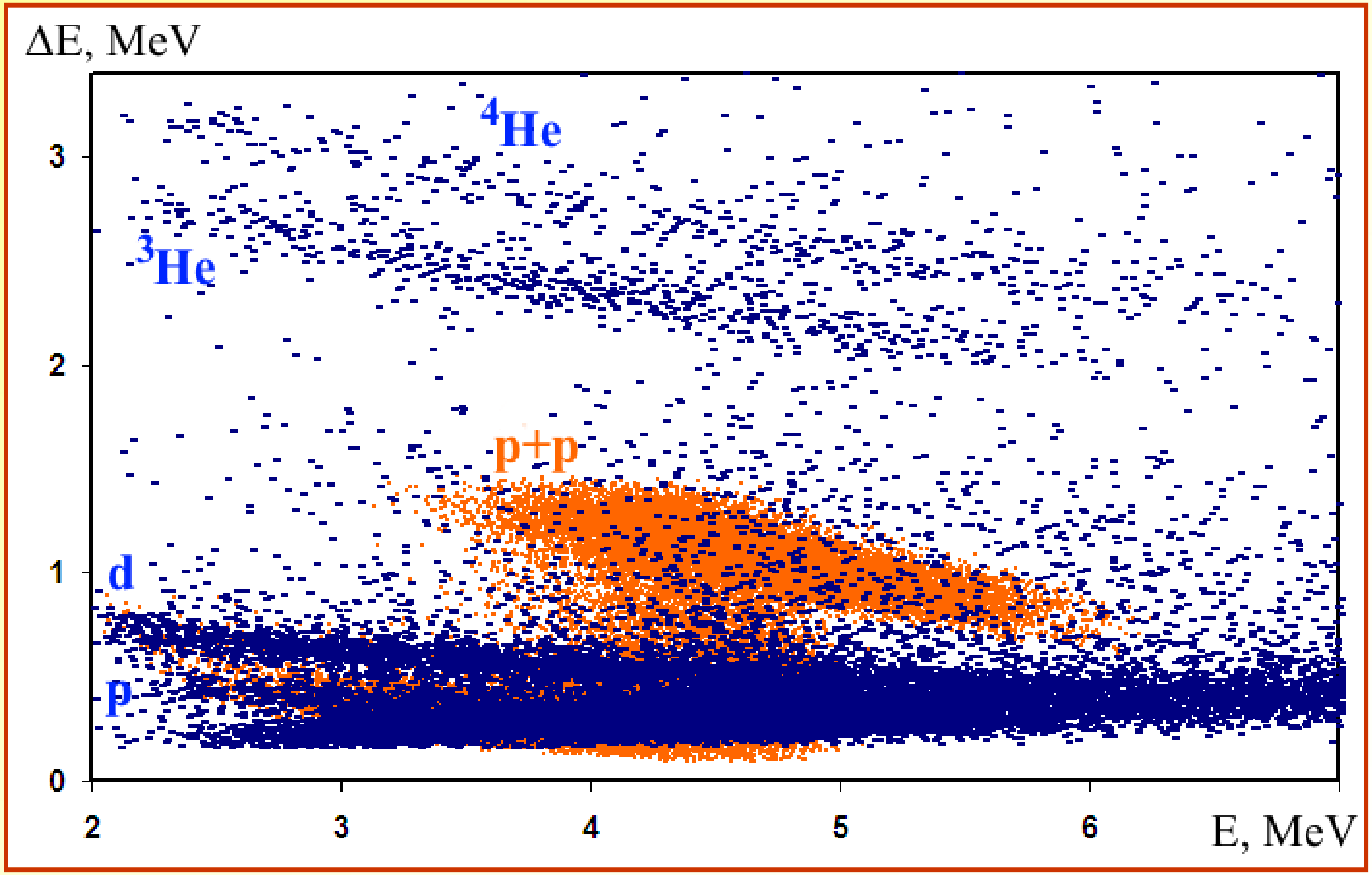
The shape of time spectra is sensitive to values of the state energy and width, that will allow us to determine these quantities from a comparison of experimental data and simulation results

Experimental: Setup for Study
$d + {}^2\mathrm{H} \rightarrow p + p + n + n$ Reaction @ $E_d = 15$ MeV



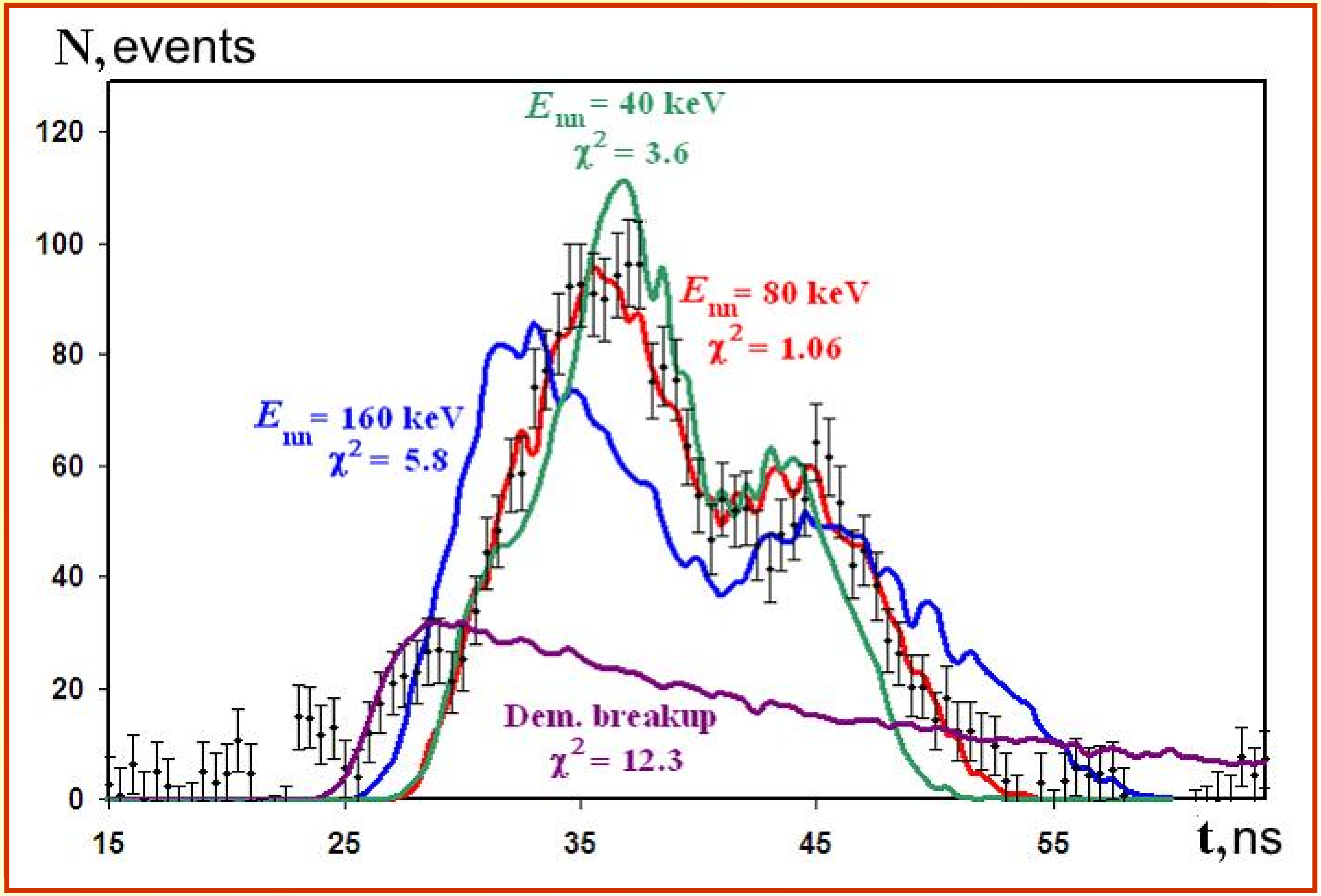
Conditions: 15 MeV deuteron beam of U120 cyclotron of SINP MSU
CD_2-target
p- and n-detectors are set at angles of ^{2}p and ^{2}n emitting
both protons are detected in one ΔE-E telescope
n-detector at 83° was used for timing calibration in dd → ^{3}He+n reaction

Experimental ΔE-E Plot and Simulated Plot for Two-Proton Events

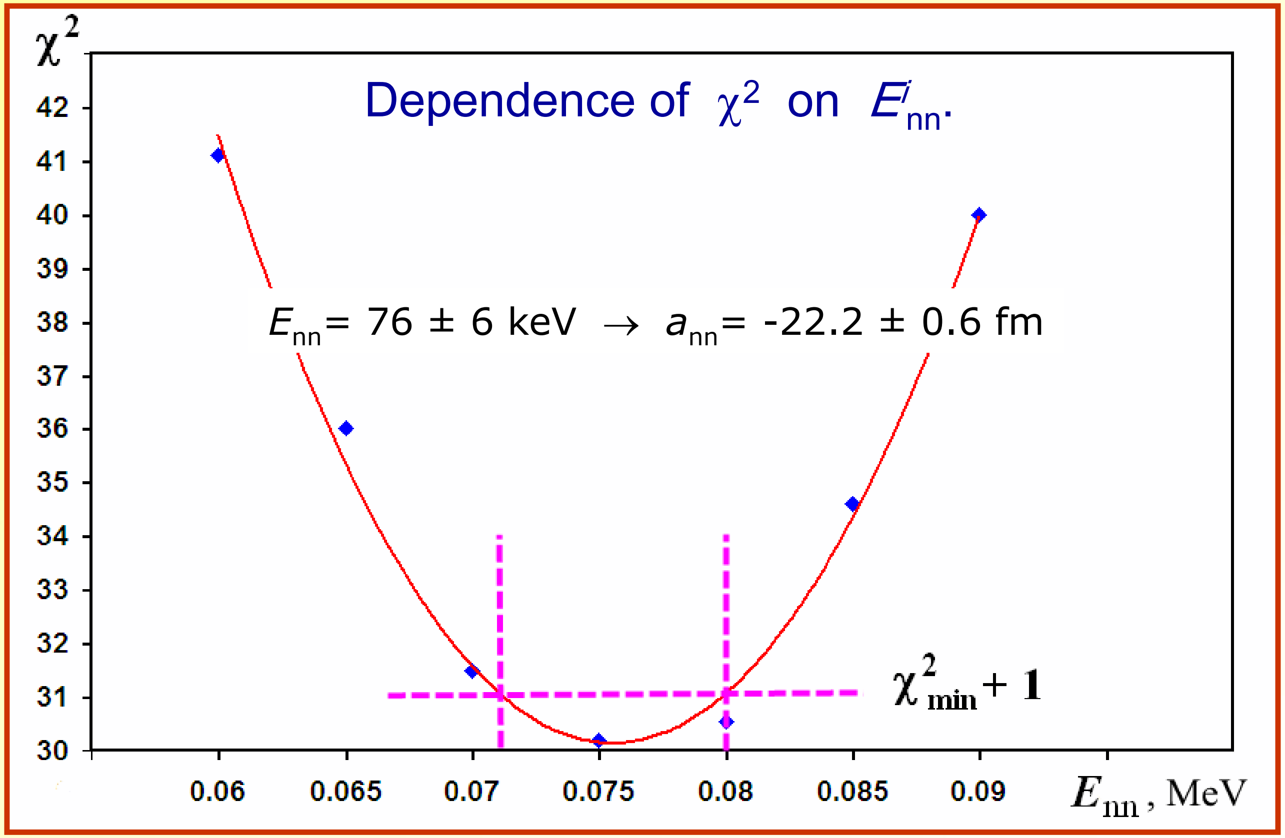


Selecting events on p+p region and determining the neutron time of flight for these events we obtained neutron timing spectrum

Experimental: Neutron Time-of-flight Spectrum vs Simulated



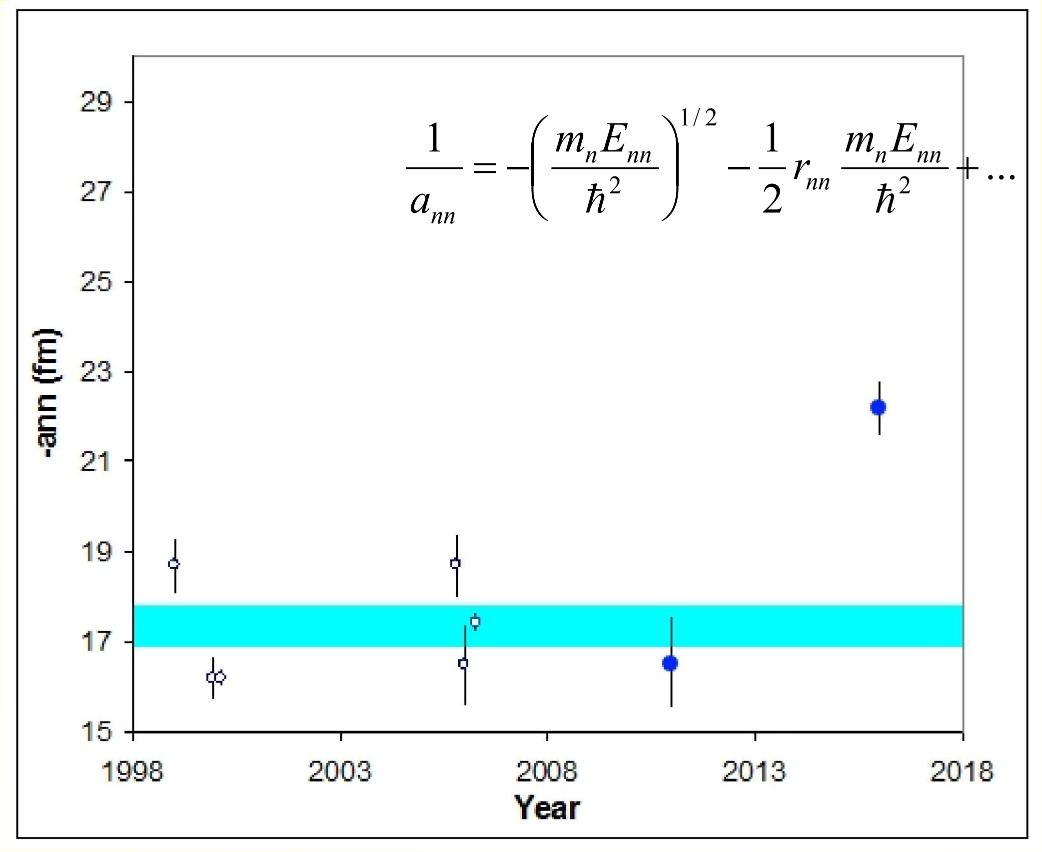
χ^2-Fitting over E_{nn}



The minimum of χ^2 determines the most probable value of the virtual state energy.

Analysis of a_{nn} data obtained in nd- and dd-breakup

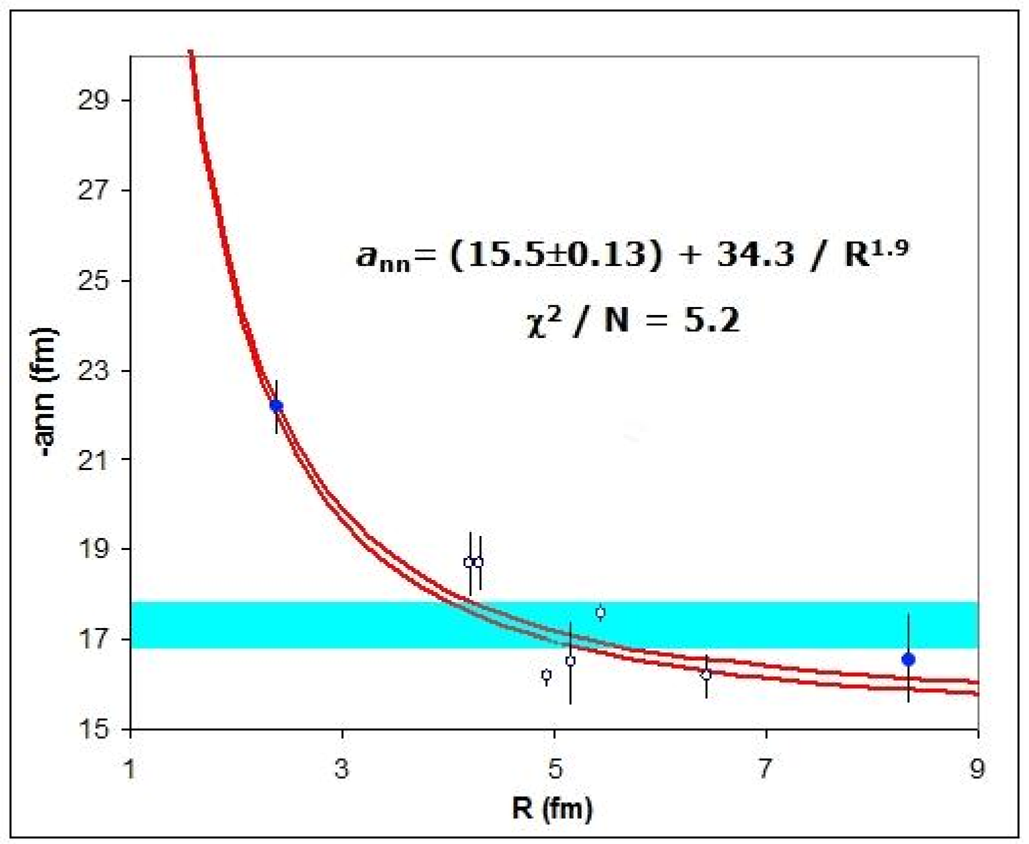
$$R \approx \tau * c * \sqrt{2\frac{(E_1+Q)(M_3+M_4)-E_1M_1}{M_3M_4}}$$



For each experiment we introduced parameter R which corresponds to distance between *nn* pair and proton (or diproton in dd experiment) for arbitrary time interval

Analysis of a_{nn} data obtained in nd- and dd-breakup

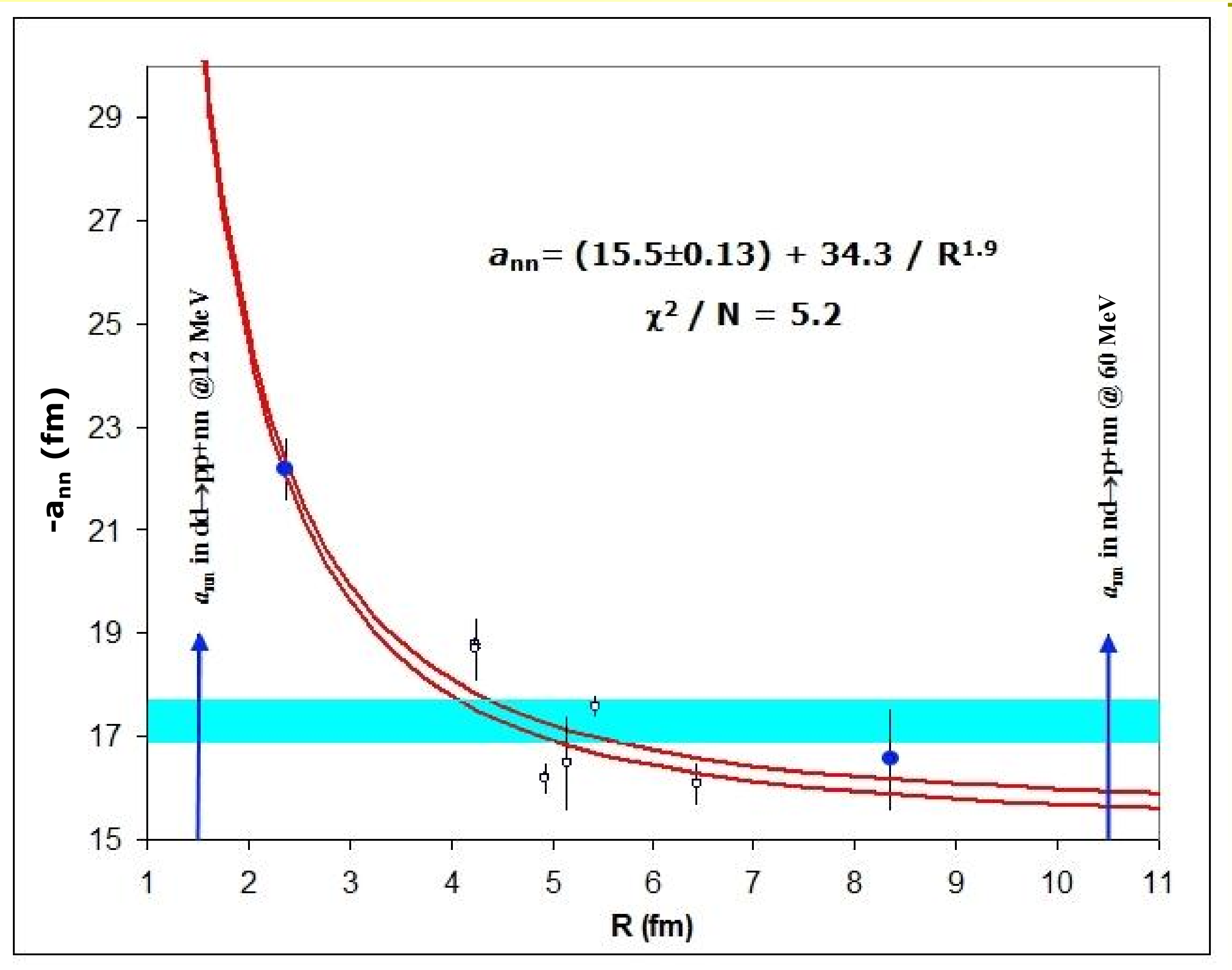
$$R \approx \tau * c * \sqrt{2\frac{(E_1+Q)(M_3+M_4)-E_1M_1}{M_3M_4}}$$



The larger is parameter R, the faster the fragments emerge from the interaction region, and the less is the effect of interaction between nn pair and the charged fragment.

Thus, it can be assumed that the data for large values of R (the asymptotics of the curve) are not affected by this interaction and more consistent with pure n-n interaction.

Possible Experiments on a_{nn} Determination in Reactions with Different R-Parameters



Conclusions

- *NN* Scattering Lengths and Virtual State Energies are very sensitive tools for studying QSB effect
- The Low Energy Parameters of *nn*-Interaction were determined in *nd* breakup reaction at $E_n = 40$ MeV at RADEX Neutron Channel of INR

$$E_{\mathrm{nn}} = 129 \pm 14 \text{ keV and } a_{nn} = -16.6 \pm 0.9 \text{ fm.}$$

- These Parameters were also determined in $d + {}^2\mathrm{H} \rightarrow n + n + p + p$ reaction at E_{d}=15 MeV at SINP MSU:

$$E_{\mathrm{nn}} = 76 \pm 6 \text{ keV}; \; a_{\mathrm{nn}} = -22.2 \pm 0.6 \text{ fm.}$$

- The obtained values of scattering lengths were compared with experimental values of ${}^1S_0$ *nn*-scattering length obtained in *nd*-breakup reaction.
- One can conclude that the difference in scattering lengths obtained under different kinematic conditions can be explained by the influence of 3N-forces depending on the relative velocity between the *nn*-pair and the charged fragment.