Few-body systems and nuclear forces

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A ROZWÓJ KRAJOWEJ INFRASTRUKTURY BADAWCZEJ

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Few-nucleon physics – hot topics

Few-nucleon physics – „classical understanding of nuclear physics – nucleons are interacting via the meson exchanges

In reactions we are focused on:

- NN interaction

Various new concepts and models have been derived recently: semi-phenomenological models from the Granada group, the JISP16, the Daejeon16, the chiral Opt-interaction, etc.

Chiral forces – new models proposed

in 2017 - the Moscow(Idaho)-Salamanca group (R.Machleidt, D.R.Entem, Y.Nosyk) N^4LO,

in 2018 - the Bochum-Bonn group (P. Reinert, H. Krebs, and E. Epelbaum) N^4LO+

- 3N and 4N interaction (the Bochum-Bonn group H.Krebs, and E.Epelbaum)

- Electromagnetic and weak currents – models are much less advanced and study of (chiral) many-body currents is at the initial phase

In general description of 2N, 3N, 4N reactions is satisfying, of course still some open problems exist, but investigations are nowadays focused on **DETAILS**

1. Interesting physics

How accurately can we describe nuclear phenomena without referring to quark-gluon degrees of freedom?

Answer requires testing new models of the nuclear interaction.

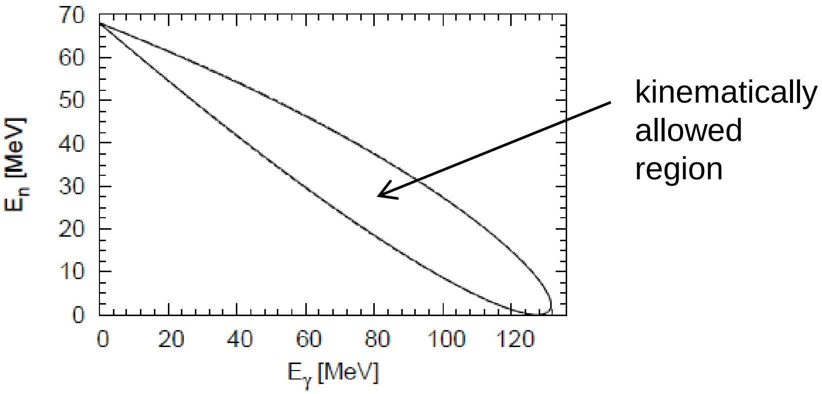
Currently a lot of attention is given to

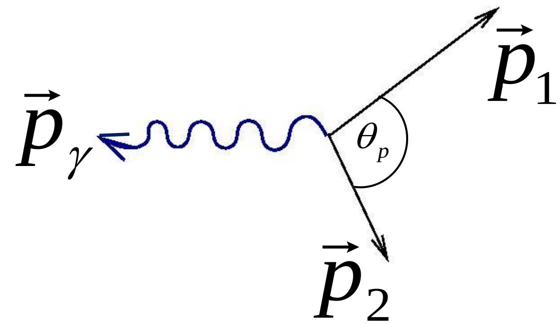
- neutron-neutron interaction
- charge dependence of three nucleon force
- consistent forces and electromagnetic and weak currents

Example: Radiative pion capture on 2H and on 3H

Radiative pion capture on ^{2}H

$$\pi^- + d \rightarrow \gamma + n + n$$





$$\Gamma_{nn} = \frac{1}{2}\frac{1}{(2\pi)^2}\frac{2\pi\alpha}{f_\pi^2 M_\pi}\frac{(M'_d\alpha)^3}{\pi}\int_0^{\pi} d\theta_{p_\gamma}\sin\theta_{p_\gamma}\int_0^{2\pi} d\phi_{p_\gamma}\int_0^{E_\gamma^{max,nn}} dE_\gamma E_\gamma \frac{1}{2}M_n p$$

$$\int_0^{\pi} d\theta_p \sin\theta_p \int_0^{2\pi} d\phi_p \frac{1}{3}\sum_{m_d}\sum_{m_1,m_2}\left(|N_{+1}(m_1,m_2,m_d)|^2 + |N_{-1}(m_1,m_2,m_d)|^2 \right)$$

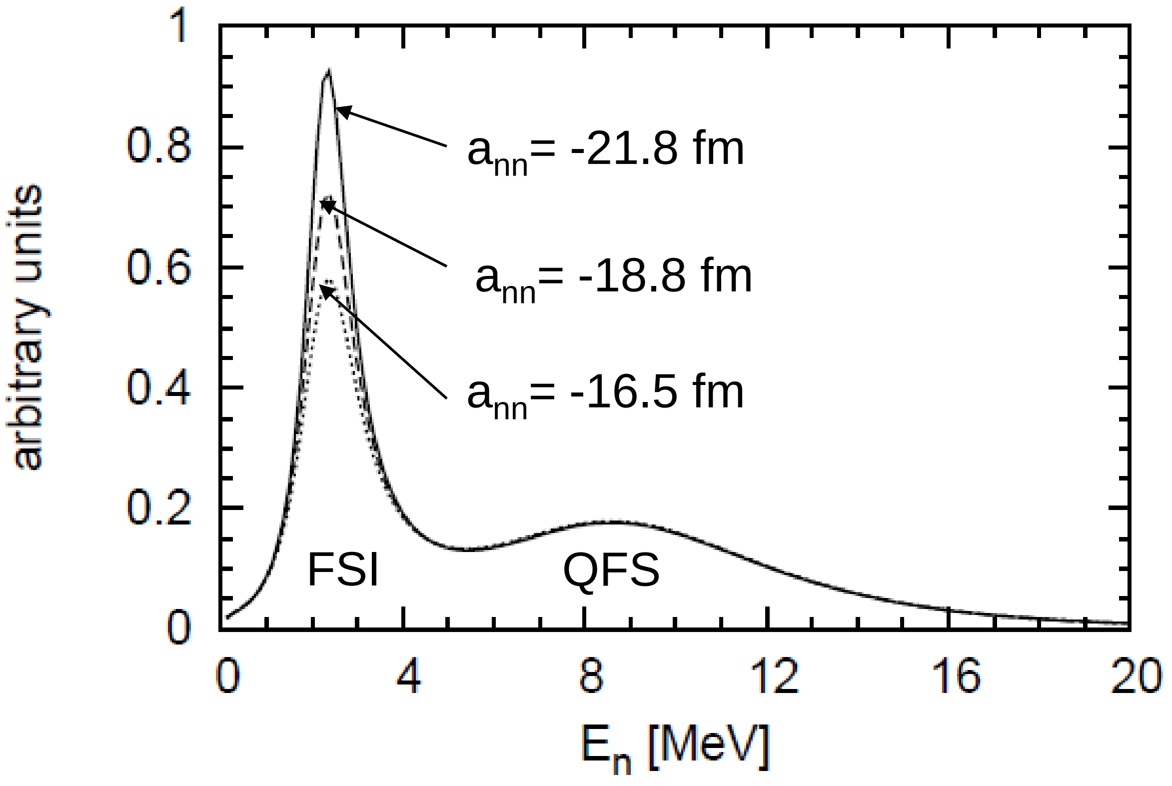
$$\vec{N} \propto \vec{\varepsilon} \cdot \left\langle \Psi_f \middle| \vec{j}_A \middle| \Psi_i \right\rangle \longleftarrow$$

Knowledge of the nuclear forces **AND** the weak current is required

Radiative pion capture on ^{2}H

$$\pi^- + d \rightarrow \gamma + n + n$$

$$d\Gamma^5_{nn} / (d\Omega_\gamma \, d\Omega_1 \, dE_1)$$

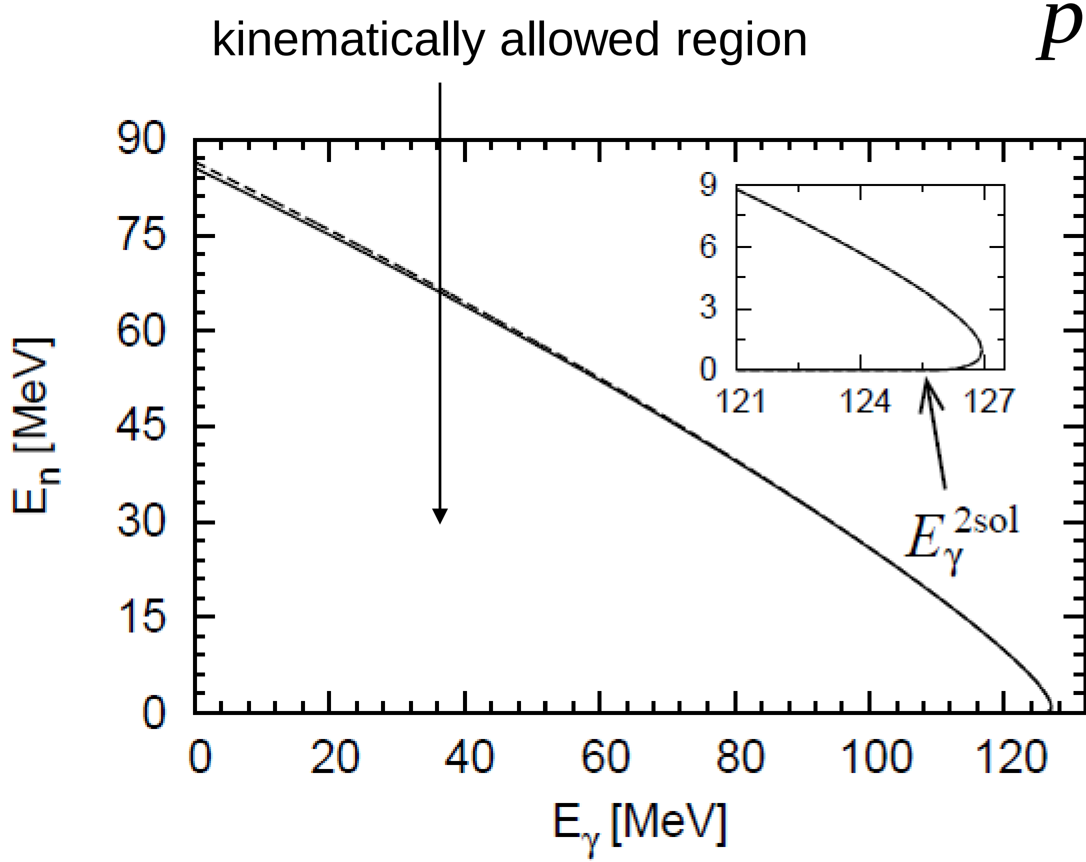


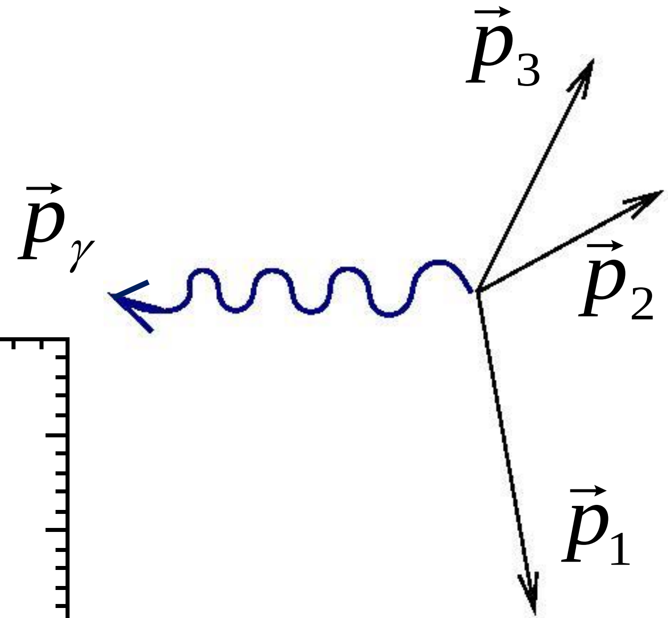
neutron-neutron potential is changed by 1 % only in the $^1S_0$ channel

neutron energy spectra for $\theta_{\gamma 1} = 179^\circ$

Radiative pion capture on ^{3}H: three-neutron breakup

$$\pi^- + {}^3\text{H} \rightarrow \gamma + n + n + n$$





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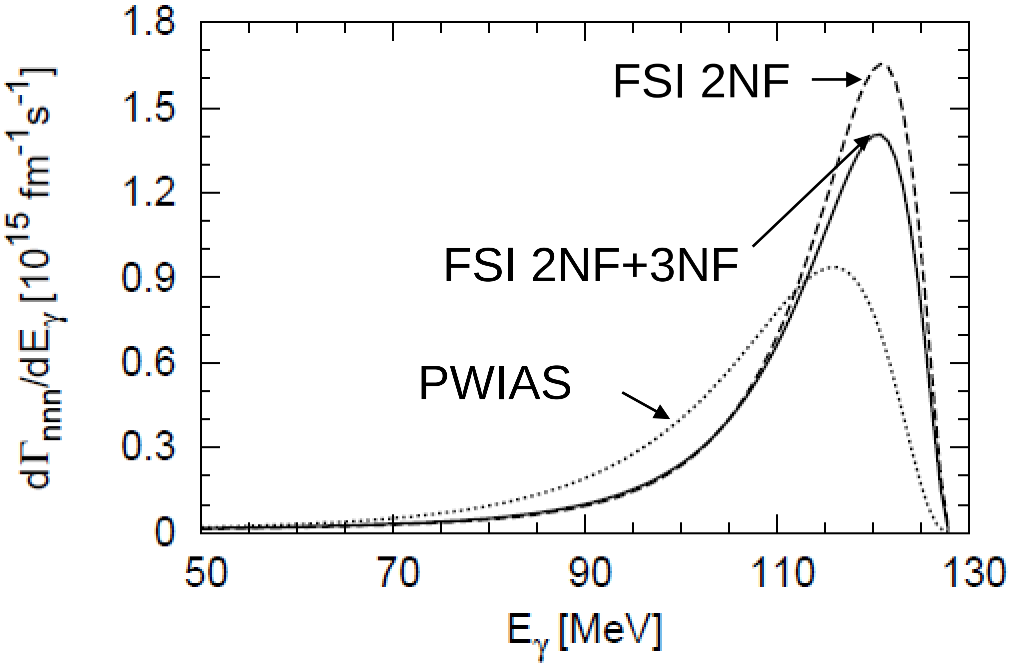


$\Gamma_{nnn} = 0.117 \times 10^{15}$ 1/s (PWIAS)
$\Gamma_{nnn} = 0.141 \times 10^{15}$ 1/s (FSI 2NF)
$\Gamma_{nnn} = 0.128 \times 10^{15}$ 1/s (FSI 2NF+3NF)

→ both FSI and 3NF are important

More: J.Golak at al., Phys.Rev. C98 (2018) 054001

2. Systematicity: spin, isospin and momentum dependence Various observables in one experiment

How to constrain the properties of many-nucleon forces ?

Beside the nuclear structure a few-nucleon scattering is a good field to study the dynamical aspects of 3NFs. Currently from theoretical side:

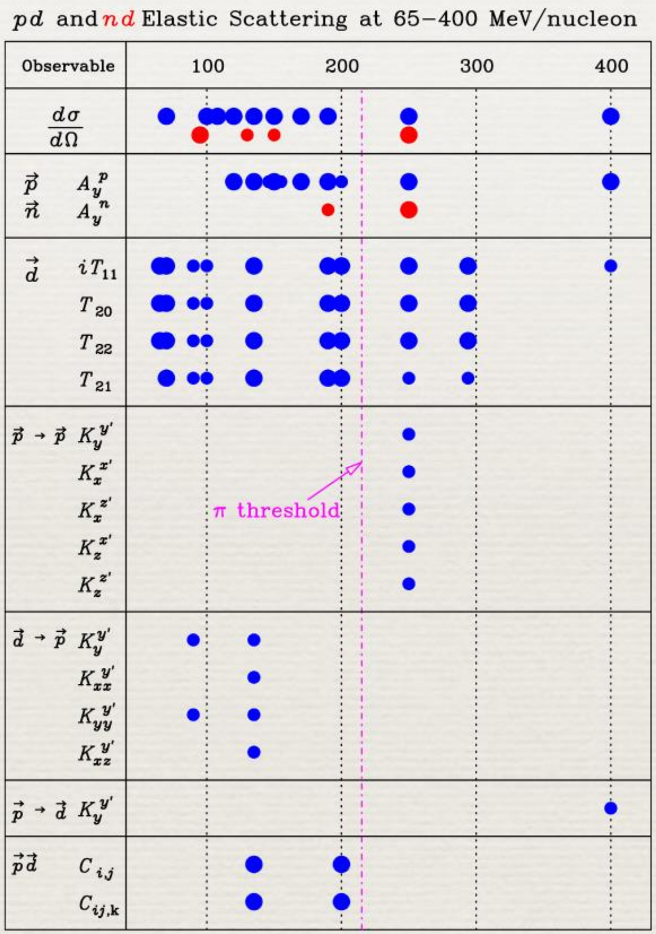
- 2N and 3N scattering is solved,
- 4N scattering is nearly solved (A.Deltuva),
- 5N scattering is attacked (n-4He R.Lazauskas).

Big progress is expected in the field.

Spin structure of three-nucleon forces is important (and complex) → spin observables are needed.

But what is an experimental situation for few-nucleon elastic scattering ?

2. Systematicity: spin, isospin and momentum dependence
Various observables in one experiment



~2018

- **High precision data of**
  ***dσ/dΩ* & Spin Observables**
  from RIKEN, RCNP, KVI, IUCF
- **Energy dependent data**
  - √ ***dσ/dΩ***
  - √ **Proton Analyzing Power**
  - √ **Deuteron Analyzing Powers**

Actually, Polish team (UJ, UŚl, IFJ,) – St.Kistryn, E.Stephan, K.Bodek, A.Kozela, I.Ciepał and many others

Situation is much worse for 4N,5N scattering

But even for 2N scattering there is a room for new experiments

(dream: neutron-neutron scattering data)

Courtesy of K.Sekiguchi

2. Systematicity: spin, isospin and momentum dependence Various observables in one experiment

There is plenty of nucleon-nucleon data (around 3500 data points in range 0-350 MeV), however beside the cross section and observables with one or two particles polarized not many more complex observables have been measured.

Do we really need them ?

Nobody knows.

Observables are used to fix potential parameters.

But what if observables are correlated ? → parameters can be biased → potentials are wrong (OK, not VERY accurate).

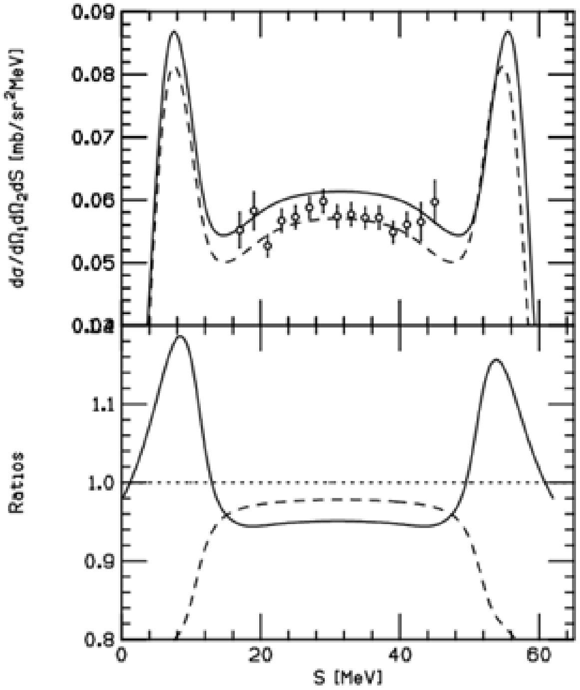
Independent check of fitting method (e.g. the Nijmegen PWA) requires 9 observables measured at the same energy and the same scattering angle.
No such data exist !
(at low energies there is one experiment from PSI at E=260 MeV but some of data are controversial and have been removed e.g. from the Granada database)

Possible measurements at CCB ? But requires polarization measurements …

3. Systematicity: walk through the phase space

- few-nucleon phase space is enough rich to study various contributions to observables

Example: relativistic effects in the deuteron break-up process - dynamical effects vs kinematical effects



N(d,NN)N
at En=65 MeV

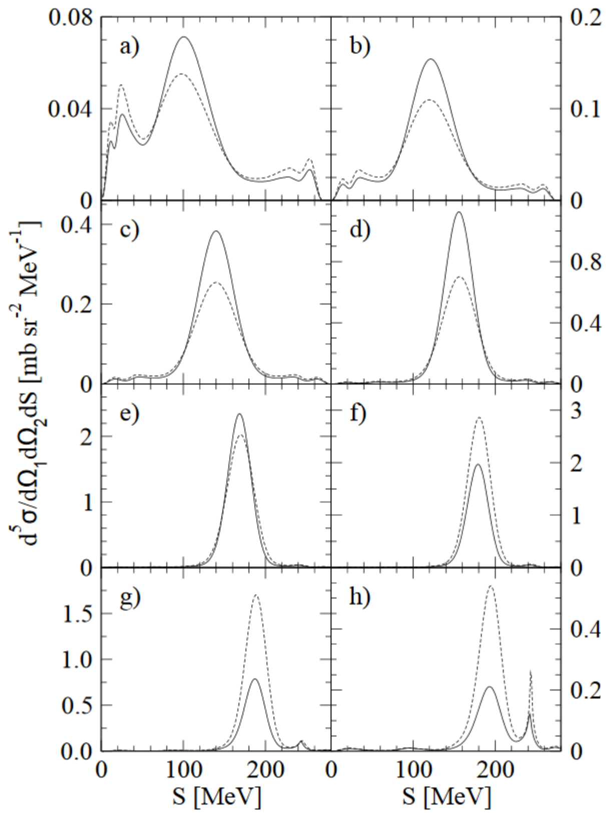
$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS} = \Big(\sum_{m_{in},m_{out}} |<\phi_0|U_0|\phi>|^2 \Big) \rho_{kin}$$

FIG. 2: Five-fold differential cross section $d^5\sigma/d\Omega_1 d\Omega_2 dS$ as a function of arc-length S for the SSS configuration (see text) of d(p,pp)n reaction at 65 MeV. The lab. angles of the outgoing protons are $\theta_1 = \theta_2 = 54^\circ$ and $\phi_{12} = 120^\circ$. The solid and dashed lines are the results of the nonrelativistic and relativistic Faddeev calculations based on the NN potential CDBonn. The 65 MeV pd data are from [16]. The lower part shows the ratios of the relativistic and nonrelativistic phase-space factors (dashed line) and of the cross sections divided by the corresponding phase-space factor (solid line).

H.Witała et al., Phys.Lett. B634 (2006) 374

3. Systematicity: walk through the phase space

Example: relativistic effects in the deuteron break-up process – nonrelativistic predictions vs relativistic ones



N(d,NN)N
at En=200 MeV

Relativistic potential (obtained from the nonrelativistic CD-Bonn)
(new Kharkov force in 2018)
Boost of the potential
Wigner rotations

FIG. 5: The five-fold cross section $\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS}$ for $d(n, n_1 n_2)p$ breakup reaction at $E_n^{lab} = 200$ MeV at fixed $\theta_2 = 37.5°$, $\phi_{12} = 180°$ and varying θ_1: a) $\theta_1 = 27.5°$, b) $\theta_1 = 32.5°$, c) $\theta_1 = 37.5°$, d) $\theta_1 = 42.5°$, e) $\theta_1 = 47.5°$, f) $\theta_1 = 52.5°$, g) $\theta_1 = 57.5°$, h) $\theta_1 = 62.5°$. The nonrelativistic and relativistic cross sections are shown by dashed and solid lines, respectively. The calculations are based on the CD Bonn potential (see text).

R.S. et al., Eur. Phys. J. A30 (2006) 369

4. Systematics in systems 2N, 3N, 4N,…

- Unavoidable to understand many-body forces, currents (1-body current, 2-body current, 3-body current, …), correlations, structure of nuclei, etc.

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5. Understanding theoretical methods

- SRG methods, induced 3NF
- Applicability of low momentum potentials to processes at higher energies
- Regularization of chiral forces

6. Precision

- Competition between experimental and theoretical uncertainties

7. Nuclear forces and currents from χEFT

- Role of various components of chiral interactions and currents.

Coda

- Physics !
- Polarizations ! – cross section is not enough
- Systematicity ! – one point is not enough
- Multitasking ! – one system is not enough
- Precision ! – of course, we are looking for details
- Crossing limits ! – do neutron-neutron scattering

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- Yes, it is difficult !
- But definitely worth doing !

More in papers:

S.Binder et al., Phys. Rev. C93, 044002 (2016)
S.Binder et al., Phys. Rev. C98, 014002 (2018)
E.Epelbaum et al., arXiv nucl-th 1807.02848
J.Golak et al., Phys. Rev. C98 015501 (2018)
R.Skibiński et al., Phys.Rev. C98 014001 (2018)
R.Skibiński et al., Phys.Rev. C97 014002 (2018)