The Kharkov Potential in the Theory of $2N-$ and $3N-$ Systems with Solving the Relativistic Faddeev equations

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The Kharkov potential is a recent field theoretical model of nucleon-nucleon (NN) interaction that has been built up in the framework of the instant form of relativistic dynamics starting with the total Hamiltonian of interacting meson and nucleon fields and using the method of unitary clothing transformations. The latter connect the representation of “bare” particles (BPR) and the representation of “clothed” particles (CPR), i.e., the particles with physical properties. Unlike our preceding explorations we show fresh results with best-fit values for adjustable parameters revisited.

To the memory of M. I. Shirokov
Excellent Scientist and
Modest Person

Contents

Some Recollections

In many textbooks on nuclear physics we encounter

$$H = K + V,$$

K one-body operator of kinetic energy, interaction between nucleons

$$V = \sum_{i<j}^{N} V(i,j) + \sum_{i<j<k}^{N} V(i,j,k) + \cdots$$

with two-body $V(i,j)$, three-body $V(i,j,k)$ forces, etc.
$(i,j,k = 1,2,\cdots,N)$.
The UCT method (Dubovik, E.A. and Shebeko, A.V. (2010) *Few Body Syst.* **48** 109; Shebeko, A. (2012) In: *Advances in Quantum Field Theory*, ed. S. Ketov (InTech), P.3.) allows us to construct such interactions on one and the same physical footing. In this respect, we are starting with the Hamiltonian for Yukawa-type couplings between $\pi-, \eta-, \delta-, \omega-, \rho-, \sigma-$ mesons and nucleons(antinucleons).

As an illustration,

$$V_{\rm s} = g_{\rm s}\int d\vec{x}\,\bar{\psi}(\vec{x})\psi(\vec{x})\varphi_{\rm s}(\vec{x}) \quad V_{\rm ps} = ig_{\rm ps}\int d\vec{x}\,\bar{\psi}(\vec{x})\gamma_5\psi(\vec{x})\varphi_{\rm ps}(\vec{x})$$

$$V_{\rm v} = V_{\rm v}^{(1)} + V_{\rm v}^{(2)}, \quad V_{\rm v}^{(1)} = \int d\vec{x} H_{sc}(\vec{x}), \quad V_{\rm v}^{(2)} = \int d\vec{x} H_{nonsc}(\vec{x})$$

$$H_{sc}(\vec{x}) = g_{\rm v}\bar{\psi}(\vec{x})\gamma_\mu\psi(\vec{x})\varphi_{\rm v}^{\mu}(\vec{x}) + \frac{f_{\rm v}}{4m}\bar{\psi}(\vec{x})\sigma_{\mu\nu}\psi(\vec{x})\varphi_{\rm v}^{\mu\nu}(\vec{x})$$

$$H_{nonsc}(\vec{x}) = \frac{g_{\rm v}^2}{2m_{\rm v}^2}\bar{\psi}(\vec{x})\gamma_0\psi(\vec{x})\bar{\psi}(\vec{x})\gamma_0\psi(\vec{x}) + \frac{f_{\rm v}^2}{4m^2}\bar{\psi}(\vec{x})\sigma_{0i}\psi(\vec{x})\bar{\psi}(\vec{x})\sigma_{0i}\psi(\vec{x})$$

$\varphi_{\rm v}^{\mu\nu}(\vec{x}) = \partial^\mu\varphi_{\rm v}^{\nu}(\vec{x}) - \partial^\nu\varphi_{\rm v}^{\mu}(\vec{x})$ tensor of vector field in Schrödinger (S) picture.

Here we encounter scalar H_{sc} and nonscalar H_{nonsc} contributions to interaction densities of ρNN and ωNN couplings

$$U_F(\Lambda, a)H_{sc}(x)U_F^{-1}(\Lambda, a) = H_{sc}(\Lambda x + a)$$

$$U_F(\Lambda, a)H_{nonsc}(x)U_F^{-1}(\Lambda, a) \neq H_{nonsc}(\Lambda x + a)$$

It requires a special consideration ...

Method of UCTs in Action

Method in question is aimed at expressing a field Hamiltonian through the so-called clothed-particle creation (annihilation) operators α_c ,e.g., $a_c^\dagger(a_c)$ [mesons], $b_c^\dagger(b_c)$ [nucleons] and $d_c^\dagger(d_c)$ [antinucleons] via UCTs $W(\alpha_c) = W(\alpha) = \exp R$, $R = -R^\dagger$ in similarity transformation

$$\alpha = W(\alpha_c)\alpha_c W^\dagger(\alpha_c)$$

that connect primary set α in bare-particle representation (BPR) with the new operators in CPR.

A key point of clothing procedure in question is to remove so-called bad terms from Hamiltonian

$$H \equiv H(\alpha) = H_F(\alpha) + H_I(\alpha) = W(\alpha_c)H(\alpha_c)W^\dagger(\alpha_c) \equiv K(\alpha_c),$$

By definition, such terms prevent physical vacuum $|\Omega\rangle$ (H lowest eigenstate) and one-clothed-particle states $|n\rangle_c = a_c^\dagger(n)|\Omega\rangle$ to be H eigenvectors for all n included. In this context all primary Yukawa-type (trilinear) couplings shown above should be eliminated.

At this point, one can address the so–called Belinfante ansatz

$$\vec{N}_{bel} = -\int \vec{x}H(\vec{x})d\vec{x}$$

which is helpful for a simultaneous block diagonalization of Hamiltonian and boost

Respectively, let us write for boson–fermion system

$$H_I(\alpha) = V(\alpha) + V_{ren}(\alpha)$$

with primary (trial) interaction $V(\alpha) = V_{bad} + V_{good}$ "good" (e.g., $\in [k.2]$) as antithesis of "bad" while $V_{ren}(\alpha) \sim [1.1] + [0.2] + [2.0]$ "mass renormalization counterterms". It turns out that latter are important to ensure RI as a whole, i.e., in Dirac sense. In order to compare our calculations with those by Bonn collaboration (Machleidt, Holinde, Elster) we have employed $V(\alpha) = V_{\rm s} + V_{\rm ps} + V_{\rm v}$. Then clothing itself is prompted by

$$H(\alpha) = K(\alpha_c) \equiv W(\alpha_c)[H_F(\alpha_c) + V_{\rm v}(\alpha_c) + V_{ren}(\alpha_c)]W^\dagger(\alpha_c)$$

or

$$K(\alpha_c) = H_F(\alpha_c) + V_{\rm v}^{(1)}(\alpha_c) + [R, H_F] + V_{\rm v}^{(2)}(\alpha_c) + [R, V_{\rm v}^{(1)}] + \frac{1}{2}[R,[R,H_F]] + [R, V_{\rm v}^{(2)}] + \frac{1}{2}[R,[R, V_{\rm v}^{(1)}] + ...$$

and requiring $[R, H_F] = -V_{\rm v}^{(1)}$ (*) for the operator R of interest to get

$$H = K(\alpha_c) = K_F + K_I$$

with a new free part $K_F = H_F(\alpha_c) \sim a_c^\dagger a_c$ and interaction

$$K_I = \frac{1}{2}[R, V_{\rm v}^{(1)}] + V_{\rm v}^{(2)} + \frac{1}{3}[R,[R, V_{\rm v}^{(1)}]] + ...$$

Moreover, after modest effort,

$$\frac{1}{2}\left[R, V_{\rm v}^{(1)}\right](NN \to NN) = K_{\rm v}(NN \to NN) + K_{cont}(NN \to NN)$$

Operator $K_{cont}(NN \to NN)$ may be associated with a contact interaction since it does not contain any propagators
(details see in Dubovik, Shebeko, FBS. 48 (2010)). It has turned out that this operator cancels completely non–scalar operator $V^{(2)}$. Such a cancellation is a pleasant feature of the CPR. In parallel, we have

$$\vec{N}(\alpha) = \vec{B}(\alpha_c) = W(\alpha_c)\{\vec{N}_F(\alpha) + \vec{N}_I(\alpha) + \vec{N}_{ren}(\alpha)\}W^{\dagger}(\alpha_c)$$

with

$$\vec{N}_I = -\int \vec{x} V_{\rm v}(\vec{x}) d\vec{x} = -\int \vec{x}\{V_{\rm v}^{(1)}(\vec{x}) + V_{\rm v}^{(2)}(\vec{x})\} d\vec{x} = \vec{N}_I^{(1)} + \vec{N}_I^{(2)}$$

As before, we find that boost generator in CPR acquires structure similar to $K(\alpha_c)$

$$\vec{B}(\alpha_c) = \vec{B}_F + \vec{B}_I.$$

Here $\vec{B}_F = \vec{N}_F(\alpha_c)$ boost operator for noninteracting clothed particles (in our case fermions and vector mesons) and $\vec{B}_I$ incorporates contributions induced by interactions between them

$$\vec{B}_I = +\frac{1}{2}[R, \vec{N}_I^{(1)}] + \frac{1}{3}[R, [R, \vec{N}_I^{(1)}]] + \ldots$$

Relativistic Interactions in Meson–Nucleon Systems

Interaction operators

$$K_I \sim a_c^\dagger b_c^\dagger a_c b_c(\pi N \to \pi N) + b_c^\dagger b_c^\dagger b_c b_c(NN \to NN) + d_c^\dagger d_c^\dagger d_c d_c(\bar{N}\bar{N} \to \bar{N}\bar{N})$$
$$+ b_c^\dagger b_c^\dagger b_c^\dagger b_c b_c b_c(NNN \to NNN) + \ ... \ + [a_c^\dagger a_c^\dagger b_c d_c + H.c.](N\bar{N} \leftrightarrow 2\pi) + ...$$
$$+ [a_c^\dagger b_c^\dagger b_c^\dagger b_c b_c + H.c.](NN \leftrightarrow \pi NN) + ...$$

Nucleon-nucleon interaction operator

$$K_{NN} = \int d\vec{p}_1 d\vec{p}_2 d\vec{p}_1{}' d\vec{p}_2{}' V_{NN}(\vec{p}_1{}', \vec{p}_2{}'; \vec{p}_1, \vec{p}_2) b_c^\dagger(\vec{p}_1{}') b_c^\dagger(\vec{p}_2{}') b_c(\vec{p}_1) b_c(\vec{p}_2),$$

$$V_{NN}(\vec{p}_1{}', \vec{p}_2{}'; \vec{p}_1, \vec{p}_2) = -\frac{1}{2}\frac{g^2}{(2\pi)^3}\frac{m^2}{\sqrt{E_{\vec{p}_1} E_{\vec{p}_2} E_{\vec{p}_1{}'} E_{\vec{p}_2{}'}}}\delta(\vec{p}_1{}' + \vec{p}_2{}' - \vec{p}_1 - \vec{p}_2)$$
$$\times \bar{u}(\vec{p}_1{}')\gamma_5 u(\vec{p}_1)\frac{1}{(p_1 - p_1')^2 - \mu^2}\bar{u}(\vec{p}_2{}')\gamma_5 u(\vec{p}_2),$$

Corresponding relativistic and properly symmetrized NN quasipotential is

$$\tilde{V}_{NN}(\vec{p}_1{}', \vec{p}_2{}'; \vec{p}_1, \vec{p}_2) = \left\langle b_c^\dagger(\vec{p}_1{}') b_c^\dagger(\vec{p}_2{}')\Omega \mid K_{NN} \mid b_c^\dagger(\vec{p}_1) b_c^\dagger(\vec{p}_2)\Omega \right\rangle$$

or through the Feynman-like 'propagators' :

$$\tilde{V}_{NN}(\vec{p}_1{}', \vec{p}_2{}'; \vec{p}_1, \vec{p}_2) = -\frac{1}{2}\frac{g^2}{(2\pi)^3}\frac{m^2}{2\sqrt{E_{\vec{p}_1} E_{\vec{p}_2} E_{\vec{p}_1{}'} E_{\vec{p}_2{}'}}}\delta(\vec{p}_1{}' + \vec{p}_2{}' - \vec{p}_1 - \vec{p}_2)$$

$$\times\, \bar{u}(\vec{p}_1{}')\gamma_5 u(\vec{p}_1)\frac{1}{2}\left\{\frac{1}{(p_1 - p_1')^2 - \mu^2} + \frac{1}{(p_2 - p_2')^2 - \mu^2}\right\}\bar{u}(\vec{p}_2{}')\gamma_5 u(\vec{p}_2) - (1 \leftrightarrow 2). \quad (*)$$

Formula (*) determines *NN* part of OBE interaction derived earlier via Okubo-Glóckle-Múller transformation by Korchin, Shebeko [Phys. At. Nucl. **56** (1993) 1663] (cf. Fuda, Zhang. Phys. Rev. C **51** (1995) 23) taking into account pion exchange and heavy-meson exchanges.

Distinctive feature of potential (*) is the presence of covariant (Feynman-like) "propagator",

$$\frac{1}{2}\left\{\frac{1}{(p_1-p_1')^2-\mu^2}+\frac{1}{(p_2-p_2')^2-\mu^2}\right\}.$$

On the energy shell for *NN* scattering, that is

$$E_i \equiv E_{\vec{p}_1}+E_{\vec{p}_2}=E_{\vec{p}_1'}+E_{\vec{p}_2'}\equiv E_f,$$

this expression is converted into genuine Feynman propagator. It is typical of other meson-exchange interactions.

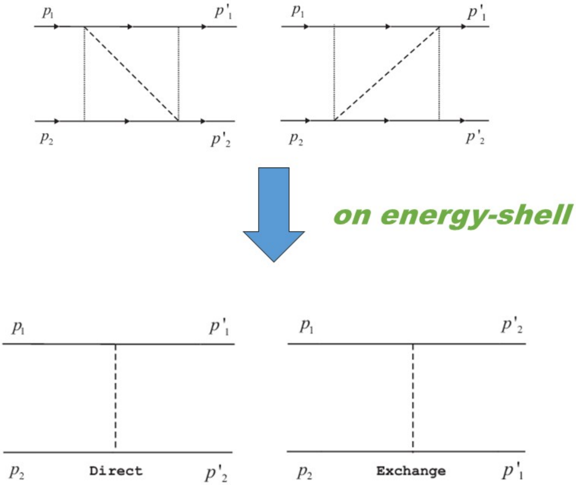


Figure 1: The one-meson-exchange off-energy-shell graphs (upper) and Feynman diagrams (lower) for NN scattering

Potential B by Bonn group can be obtained from UCT quasipotentials with help of replacements

- for boson propagators

$$[(p' - p)^2 - m_b^2]^{-1} \longrightarrow -[(\vec{p}\,' - \vec{p})^2 + m_b^2]^{-1}$$

- for cutoff functions

$$\left[\frac{\Lambda_b^2 - m_b^2}{\Lambda_b^2 - (p' - p)^2}\right]^{n_b} \longrightarrow \left[\frac{\Lambda_b^2 - m_b^2}{\Lambda_b^2 + (\vec{p}\,' - \vec{p})^2}\right]^{n_b}$$

- omitting off–energy–shell correction in tensor–tensor term

$$\frac{f_{\mathrm{v}}{}^2}{4m^2}(E_{p'} - E_p)^2 \bar{u}(\vec{p}\,')[\gamma_0\gamma_\nu - g_{0\nu}]u(\vec{p})\bar{u}(-\vec{p}\,')[\gamma^0\gamma^\nu - g^{0\nu}]u(-\vec{p}) \longrightarrow 0$$

Theory and Experiment

Table 1: The best-fit parameters for the two models.

Meson		Bonn B	UCT BONN	UCT GS
π	$g_\pi^2/4\pi$	14.4	14.633	14.3868
	Λ_π	1700	2330.4317	2316.5957
	m_π	138.03	138.03	138.03
η	$g_\eta^2/4\pi$	3	3.8712	4.7436
	Λ_η	1500	1148.3563	1186.3328
	m_η	548.8	548.8	548.8
ρ	$g_\rho^2/4\pi$	0.9	1.5239	1.4905
	Λ_ρ	1850	1470.0933	1482.9515
	f_ρ/g_ρ	6.1	5.4099	5.63504
	m_ρ	769	769	769
ω	$g_\omega^2/4\pi$	24.5	27.0059	27.0010
	Λ_ω	1850	2067.1625	2048.4847
	m_ω	782.6	782.6	782.6
δ	$g_\delta^2/4\pi$	2.488	1.8362	1.9911
	Λ_δ	2000	2283.0762	2117.1415
	m_δ	983	983	983
σ, $T=0$ ($T=1$)	$g_\sigma^2/4\pi$	18.3773 (8.9437)	18.8026 (10.7836)	18.9937 (10.8998)
	Λ_σ	2000 (1900)	1629.1474 (2123.1678)	1738.8244 (2145.0415)
	m_σ	720 (550)	722.22 (565.79)	723.64 (571.74)

Column UCT BONN (UCT GS) fits Bonn potential - Machleidt, R. *Adv. Nucl. Phys* **19**(1989) (WCJ1 - Gross, F.&Stadler, A. *Phys. Rev. C* **78** (2008))

Table 2: Deuteron and low-energy parameters. The experimental values are from Table 4.2 of Ref. {Mach89}.

Parameter	Bonn B	G&S	UCT BONN	UCT G&S	Experiment
a_s (fm)	-23.685	-23.749	-23.695	-23.728	-23.748±0.010
r_s (fm)	2.71	2.67	2.71	2.69	2.68±0.05
a_t (fm)	5.426	5.429	5.431	5.421	5.419±0.007
r_t (fm)	1.761	1.766	1.769	1.755	1.754±0.008
ε_d (MeV)	2.222	2.222	2.223	2.222	2.224575

On-Shell Calculations below the Pion Production Threshold

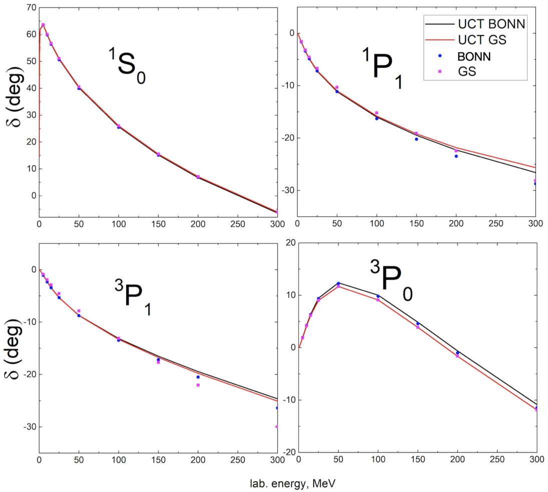


Figure 2: Neutron-proton phase-shifts for the uncoupled partial waves vs the nucleon kinetic energy in the lab. frame

On-Shell Calculations below the Pion Production Threshold

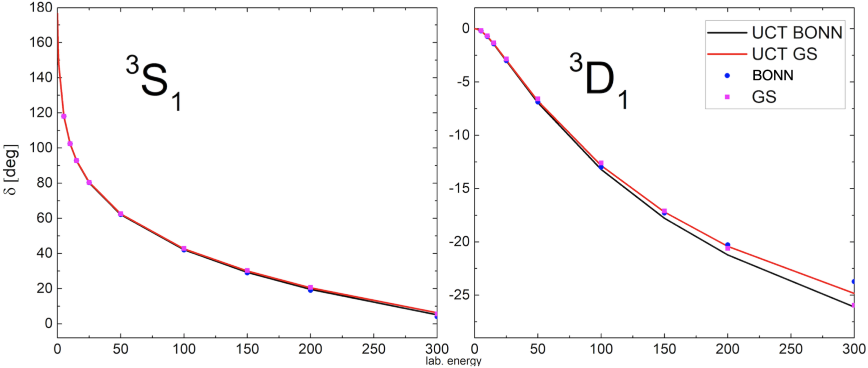


Figure 3: The same in Fig. 2 but for the coupled waves

Off-shell effects

Here we show off-energy-shell R-matrices $R(p', p_0)$ for first partial waves. Recall that on-shell R-matrix elements $R(p_0, p_0)$ are proportional to $tan\delta(p_0)$.

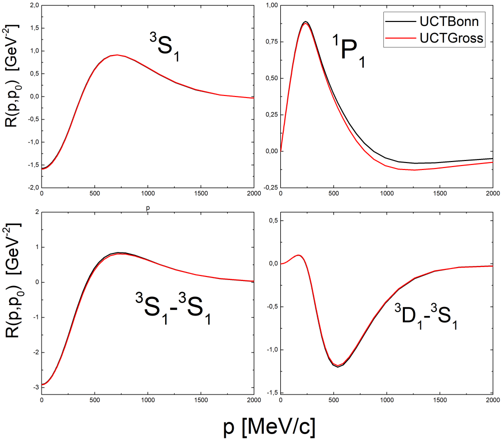


Figure 4: Half-off-shell R-matrices for uncoupled waves at lab. energy equal to 150 MeV (p0 =265 MeV)

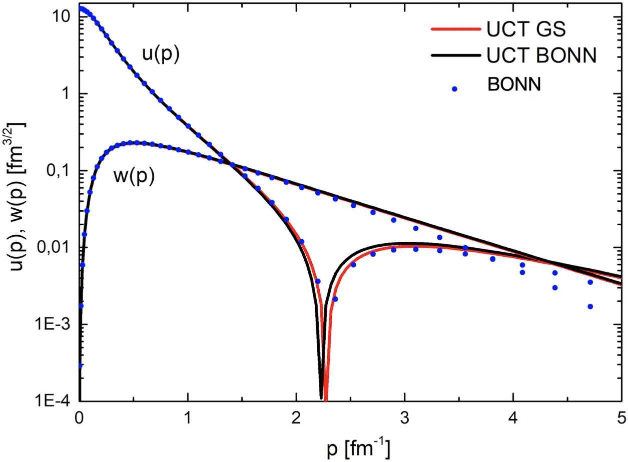


Figure 5: Deuteron wave functions $\psi_0^d(p) = u(p)$ and $\psi_2^d(p) = w(p)$. Solid(dotted) curves for Bonn Potential B (UCT) potential.

Deuteron states normalized by $\int_0^\infty p^2 dp \left[\psi_0^2(p) + \psi_2^2(p)\right] = 1.$

Clothed Particle Representation in the theory of $3N$-systems

Likely the 2-body case the eigenvalue problem in the CPR can be formulated projecting equation

$$H|\Psi\rangle = E|\Psi\rangle, \tag{1}$$

where the state $|\Psi\rangle$ belongs to $3N$ sector of Fock space as

$$\langle 123|H|\Psi\rangle = E\Psi(1,2,3). \tag{2}$$

Here $H = K_F + K_I$ with 2-body interactions K_I and $\Psi(1,2,3) \equiv \langle 123|\Psi\rangle$. Doing so and taking into account that operators b_c destroy physical vacuum $|\Omega\rangle$, *i.e.*, $b_c|\Omega\rangle = 0$, we obtain

$$(E_1 + E_2 + E_3)\Psi(1,2,3) + \langle 123|V_1 + V_2 + V_3|\Psi\rangle = E\Psi(1,2,3) \tag{3}$$

with $E_i = \sqrt{\mathbf{p}_i^2 + m^2}$, $V_1 = \tilde{V}_{NN}(2,3)$, $V_2 = \tilde{V}_{NN}(1,3)$, $V_3 = \tilde{V}_{NN}(1,2)$ and

$$\tilde{V}_{NN}(i,j) = -V_{NN}(i'\,j';i\,j) + V_{NN}(i'\,j';j\,i) - V_{NN}(j'\,i';j\,i) + V_{NN}(j'\,i';i\,j) \tag{4}$$

Remind also that, by definition, $|123\rangle = b_c^\dagger(1) b_c^\dagger(2) b_c^\dagger(3)|\Omega\rangle$ and operators b_c meet commutation relations for fermions.
Moreover, we have the following transformation property with respect to Poincarè group Π

$$U_F(\Lambda, a) b_c^\dagger(p, \mu) U_F^{-1}(\Lambda, a) = e^{i\Lambda p a} D^{(1/2)}_{\mu' \mu}(W(\Lambda, p)) b_c^\dagger(\Lambda p, \mu'),$$

$$\forall \Lambda \in L_+ \ \text{ and arbitrary spacetime shifts } a = (a^0, \mathrm{a}),$$

with D-function whose argument is Wigner rotation $W(\Lambda, p)$,
L_+ homogeneous (proper) orthochronous Lorentz group,
correspondence $(\Lambda, a) \to U_F(\Lambda, a)$ realizes unitary irreducible representation of Π. This property allows one to get the corresponding matrix elements in arbitrary frame.

Triton Binding Energy

In the c.m.s. for Triton the Faddeev equation

$$|\psi_j\rangle = G_0 V_j |\Psi\rangle, \quad j = 1, 2, 3 \tag{5}$$

with $|\Psi\rangle = |\psi_1\rangle + |\psi_2\rangle + |\psi_3\rangle$ and the resolvent

$$G_0 = (M_T - H_0)^{-1} \tag{6}$$

has been converted into the following

$$|\psi_j\rangle = G_0 V_j^q |\Psi\rangle, \quad j = 1, 2, 3 \tag{7}$$

where the V_j^q is the so-called boosted potential .

H. Kamada, W. Glöckle, Phys. Lett. B 655 (2007)

Table 3: Triton binding energies of Kharkov potential versus other popular solutions (in MeV)

Potentials	Relativistic (Nonrelativistic)	Difference
Kharkov (UCT Bonn)	-7.799 (-7.867)	0.068
Bonn	-8.14	
CD-Bonn	-8.150(-8.248)	0.098

Nucleon Momentum Distributions

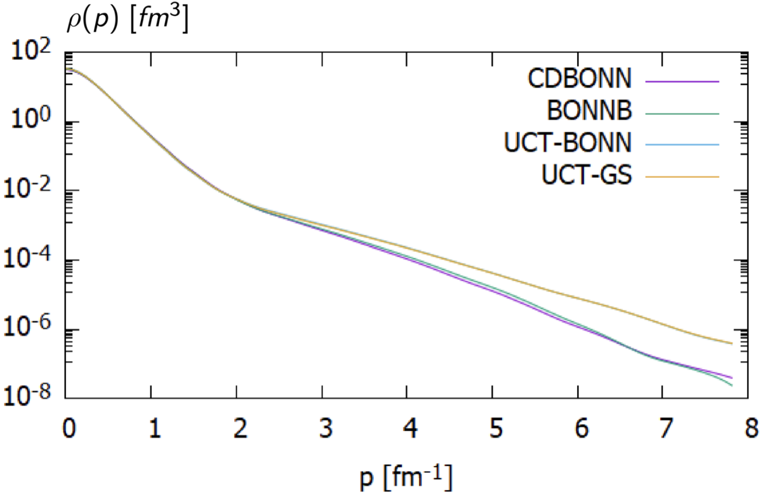
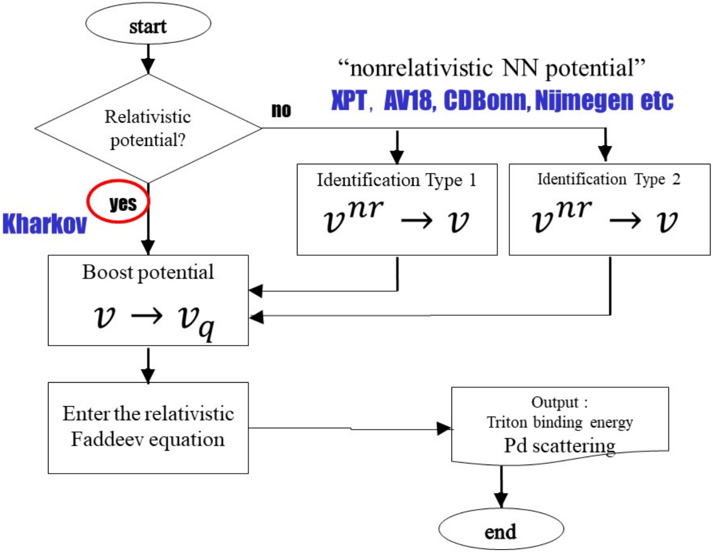


Figure 6: Triton nucleon momentum distributions

Kharkov Potential in Elastic p-d Scattering Calculations


start
Relativistic potential?
no
"nonrelativistic NN potential"
XPT, AV18, CDBonn, Nijmegen etc
Identification Type 1
$v^{nr} \to v$
Identification Type 2
$v^{nr} \to v$
yes
Kharkov
Boost potential
$v \to v_q$
Enter the relativistic Faddeev equation
Output :
Triton binding energy
Pd scattering
end

p-d scattering

- deuteron polarization observables
  vector analyzing power: iT_{11}, tensor analyzing power T_{20}, T_{21}, T_{22}
- Potentials: CDBonn, Kharkov potential (UCT GS, UCT Bonn)

Boosted correction with equation

$$V^q = \sqrt{(E_p + V)^2 + q^2} - \sqrt{(2E_p)^2 + q^2}$$

and boosted relativistic LS eq.

$$t(\mathbf{p}, \mathbf{p}'; \mathbf{q}) = V^q(\mathbf{p}, \mathbf{p}'; \mathbf{q}) + \int d\mathbf{k} \frac{V^q(\mathbf{p}, \mathbf{k}; \mathbf{q}) t(\mathbf{k}, \mathbf{p}'; \mathbf{q})}{\sqrt{(2E_{p'})^2 + \mathbf{q}^2} - \sqrt{(2E_k)^2 + \mathbf{q}^2} + i\epsilon}$$

with $E_p = \sqrt{\mathbf{p}^2 + m^2}$.

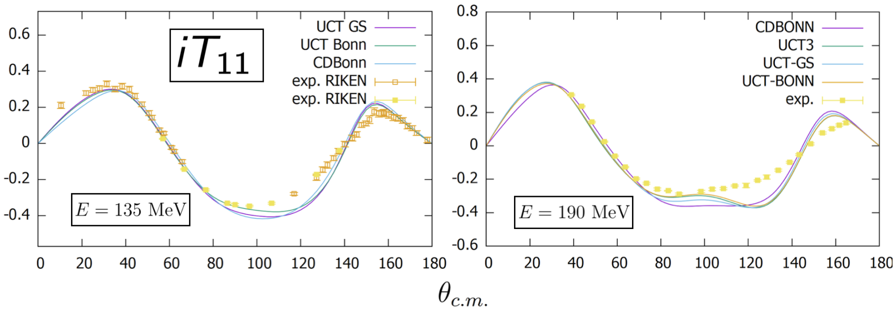


Figure 7: iT_{11} as a function of angle $\theta_{c.m.}$ for proton incident energies 135 and 190 MeV

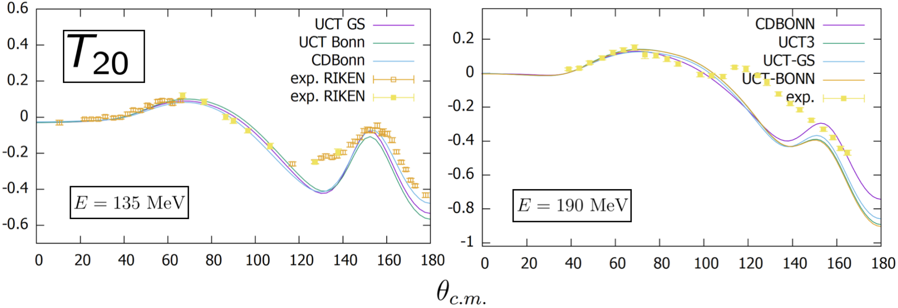


Figure 8: iT_{20} as a function of angle $\theta_{c.m.}$ for proton incident energies 135 and 190 MeV

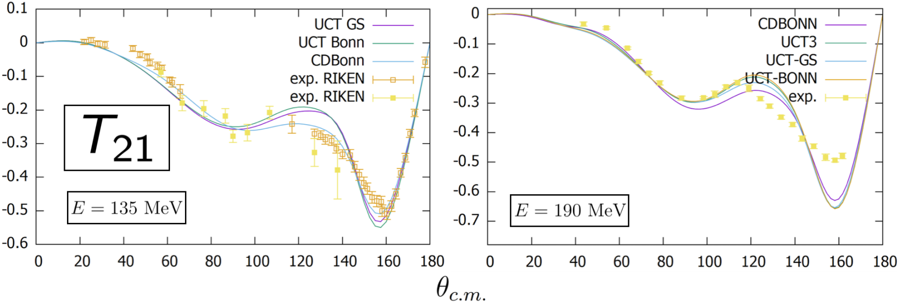


Figure 9: iT_{21} as a function of angle $\theta_{c.m.}$ for proton incident energies 135 and 190 MeV

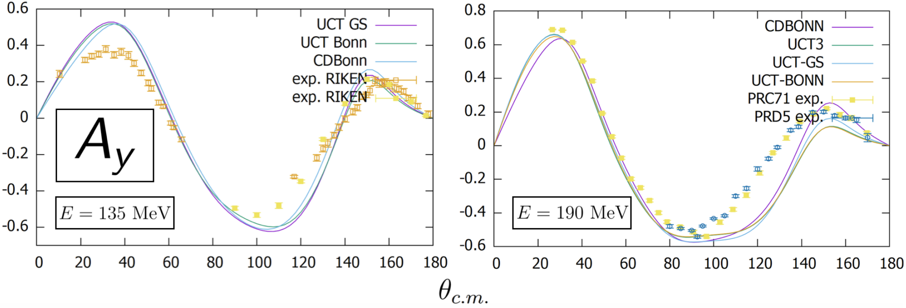


Figure 10: *Ay* as a function of angle $\theta_{c.m.}$ for proton incident energies 135 and 190 MeV

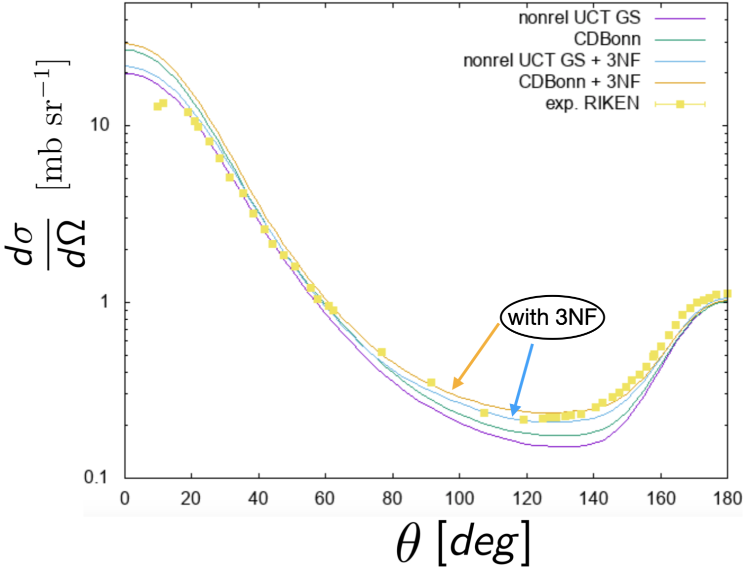


Figure 11: $\frac{d\sigma}{d\Omega}$ as a function of angle θ in c.m. for proton incident energy 135 MeV

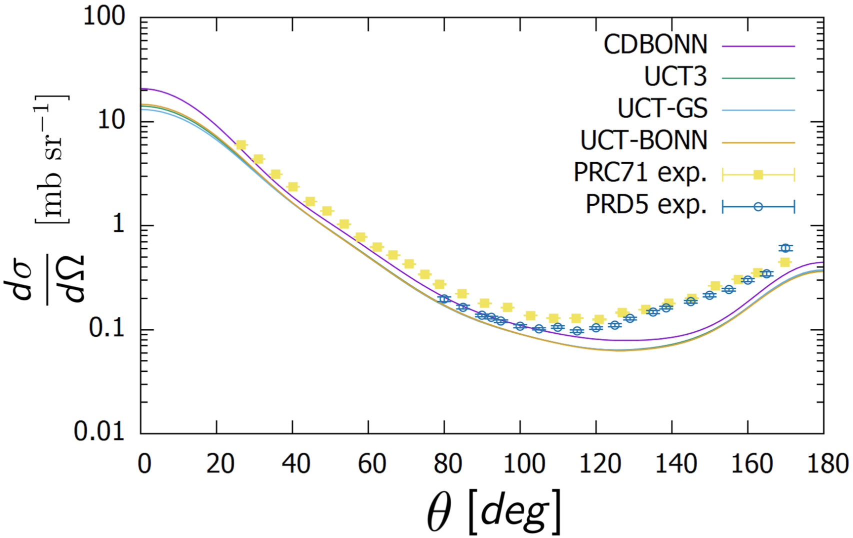


Figure 12: $\frac{d\sigma}{d\Omega}$ as a function of angle θ in c.m. for proton incident energy 190 MeV

Summary

- Starting from a total Hamiltonian for interacting meson and nucleon fields, we come to Hamiltonian and boost generator in CPR whose interaction parts consist of new relativistic interactions responsible for physical (not virtual) processes, particularly, in the system of bosons ($\pi-$, $\eta-$, $\rho-$, $\omega-$, $\delta-$ and $\sigma-$mesons) and fermions (nucleons and antinucleons).
- The corresponding quasipotentials (these essentially nonlocal objects) for binary processes $NN \to NN$, $\bar{N}N \to \bar{N}N$, etc. are Hermitian and energy independent. It makes them attractive for various applications in nuclear physics. They embody the off–shell and recoil effects (the latter in all orders of the $1/c^2$ - expansion) without addressing to any off–shell extrapolations of the $S-$matrix for the NN scattering.

- 3N operators of $b_c^\dagger b_c^\dagger b_c^\dagger b_c b_c b_c$-type should be built consistently with two-body ones. Such a work is underway.
- As a whole, persistent clouds of virtual particles are no longer explicitly contained in CPR, and their influence is included in properties of clothed particles (these quasiparticles of UCT method). In addition, we would like to stress that problem of the mass and vertex renormalizations is intimately interwoven with constructing the interactions between clothed nucleons. Renormalized quantities are calculated step by step in course of clothing procedure unlike some approaches, where they are introduced by "hands".

○ The best-fit values of adjustable parameters in the Kharkov potential have been extracted from the $n - p$ scattering data by the fitting code elaborated in the Department of Computational Physics at Saint-Petersburg University, Russia.

○ Numerical calculations with the Faddeev equations were partially performed on the interactive server at RCNP, Osaka University, Japan and on the supercomputer cluster of the JSC, Jülich, Germany.

Thank You Very Much For Your Attention