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LS force in NN system from Lattice QCD

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for HALQCD collaboration

Hadrons to Atomic nuclei HAL from Lattice QCD

Future Prospects of Hadron Physics at J-PARC and Large Scale Computational Physics

About This Work:

Recently Hadron-hadron potential from Lattice QCD was proposed.

In this talk, we will report our first attempt at determining potentials in parity odd sector including the spin-orbit force in NN system.

Table of Contents :

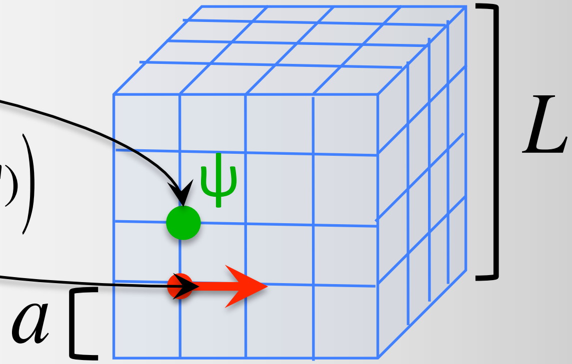
This work

Lattice QCD is strong tool of non-PT calculation of QCD

define the field on sites.

quark field ψ

Gauge field (Gauge link) $U_\mu(\vec{x}) \equiv \exp\left(ig\int_x^{x+a} dx'^\mu \ A_\mu(x')\right)$



Path-integral is performed with numerically

$$\langle O \rangle = \frac{1}{Z}\int DU\, D\psi D\bar{\psi}\ O[\psi,\bar{\psi},U]\ \exp(-S_{QCD}[\psi,\bar{\psi},U])$$

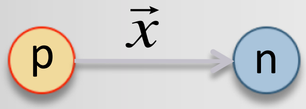
Take the limit: $a \longrightarrow 0$

Lattice QCD does not need scattering data.

We can calculate potentials based on first principle of QCD

NN potential from Lattice QCD: HAL's method

NBS wave function



$$\equiv \phi(\vec{x})$$

$$\phi(\vec{r};E) \equiv \langle 0 | N(\vec{x}) N(\vec{y}) | B=2;E \rangle$$

derivation: S.Aoki, T.Hatsuda, N.Ishii, PTP123(2010)89

Scrodinger type Equation:

"potential"

$$\left(\frac{\Delta}{m_N} + E\right)\phi(\vec{r};E) = \int d^3y\, U(\vec{r};\vec{r}')\phi(\vec{r}';E)$$

$$= \left[Vc^{(+)}(r) + V_T^{(+)}(r)S_{12} + V_{LS}^{(+)}(r)\vec{L}\cdot\vec{S} \right] P^+\phi(\vec{r};E)$$

$$+ \left[Vc^{(-)}(r) + V_T^{(-)}(r)S_{12} + V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S} \right] P^-\phi(\vec{r};E) + \mathcal{O}(\nabla^2)$$

$$Vc \equiv V_0(\vec{r}) + V_\sigma(\vec{r})(\vec{\sigma}_1\cdot\vec{\sigma}_2)$$

After expantion of the U around $\vec{r}$, with taking in to symmetries, we can obtain Okubo-Mulushck formula.

For the moment, [ ] parts has been calculated from Lattice.

ex) $^1S_0$ (L=0 S=0) case

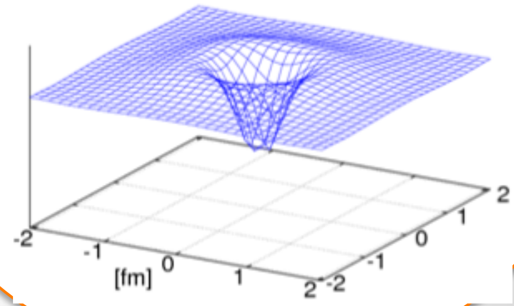
$$S_{12} = \begin{cases} \neq 0 & : S = 1 \\ = 0 & : S = 0 \end{cases}$$

$$\left(\frac{\nabla^2}{m_N} + E\right)\phi(\vec{r};E) = \left[Vc^{(+)}(r) + \cancel{V_T^{(+)}(r)S_{12}} + \cancel{V_{LS}^{(+)}(r)\vec{L}\cdot\vec{S}}\right]\phi(\vec{r};E)$$

Effective Scrodinger Equation:

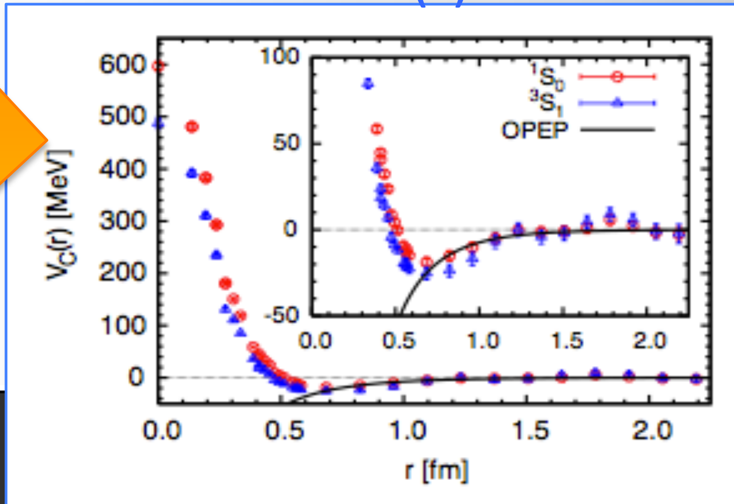
$$\left(\frac{\Delta}{m_N} + E\right)\phi(\vec{r};E) = Vc(\vec{r})\,\phi(\vec{r};E)$$

from Lattice QCD



$$Vc(r) = \left(\frac{1}{m_N}\frac{\Delta\phi(r;E)}{\phi(r;E)} + E\right)$$

Solve about Vc(r)



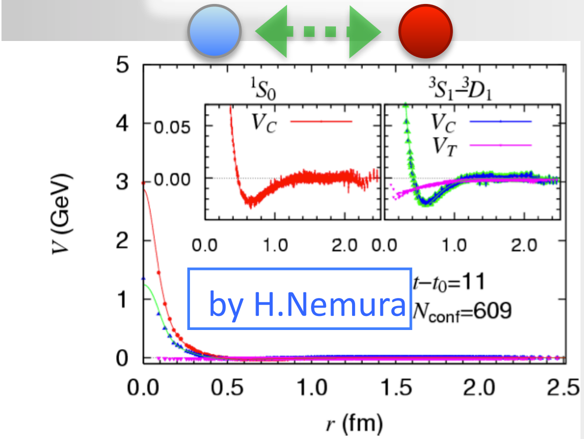
Ishii, Aoki, Hatsuda
Phys. Rev. Lett. 99, 022001 (2007)

S.Aoki T.Doi T.Hatsuda Y.Ikeda T.Inoue N.Ishii
H.Nemura K.Sasaki for HAL QCD Coll.

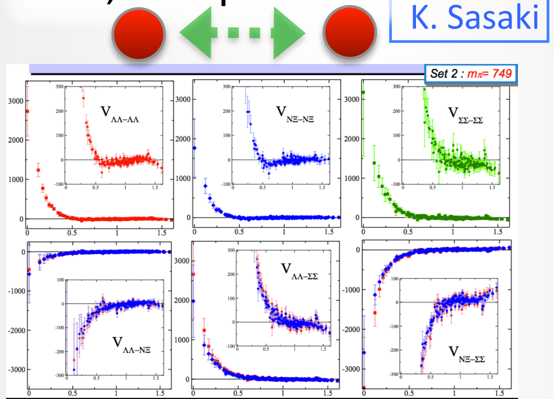
This method was extended to YY, YN, meson-baryon system and three body force.

and various potentials has been calculated.

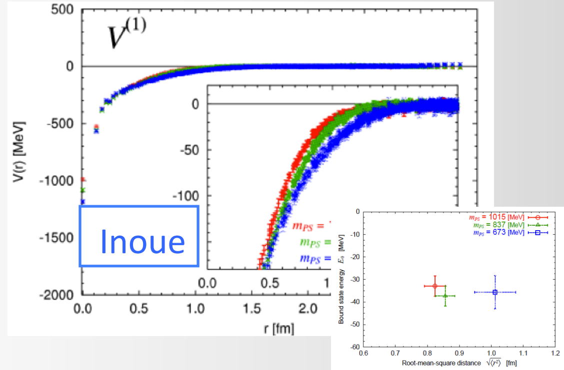
Y-N potential

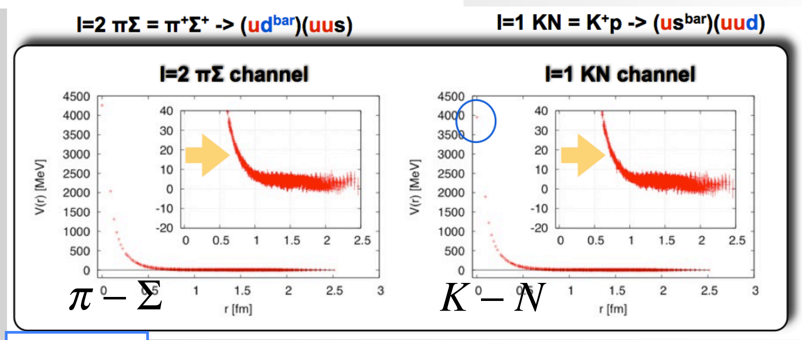


Y-N, Y-Y potential

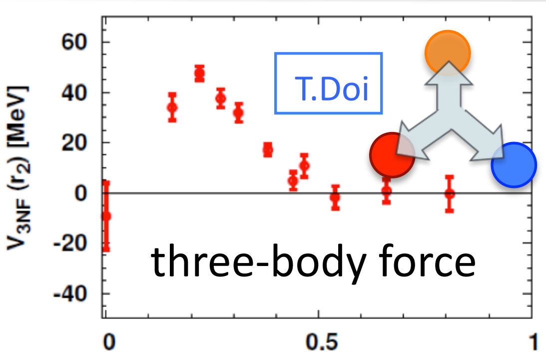


H dibaryon in SU(3)





Y. Ikeda meson-baryon potential



$Vc^{(+)}$ $V_T^{(+)}$ has been calculated from Lattice QCD.

However, $V_{LS}^{(+)}$, $Vc^{(-)}$, $V_T^{(-)}$, $V_{LS}^{(-)}$ is not yet.

$$\left(\frac{\nabla^2}{m_N}+E\right)\phi(\vec{r};E)=\left[Vc^{(+)}(r)+V_T^{(+)}(r)S_{12}+V_{LS}^{(+)}(r)\vec{L}\cdot\vec{S}\right]P^{+}\phi(\vec{r};E)$$

$$+\left[Vc^{(-)}(r)+V_T^{(-)}(r)S_{12}+V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S}\right]P^{-}\phi(\vec{r};E)+\mathcal{O}(\nabla^2)$$

These remaining potentials are ..

- needed for complete determination of potentials

Especially, spin-orbit force is important for ..

- magic numbers in nuclei
- ls-splitting of the (hyper) nuclear spectra
- super fluid in neutron star

Hadrons to Atomic nuclei HAL from Lattice QCD

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$$\left(\frac{\nabla^2}{m_N}+E\right)\phi(\vec{r};E)=\left[Vc^{(+)}(r)+V_T^{(+)}(r)S_{12}+V_{LS}^{(+)}(r)\vec{L}\cdot\vec{S}\right]P^{+}\phi(\vec{r};E)$$

$$+\left[Vc^{(-)}(r)+V_T^{(-)}(r)S_{12}+V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S}\right]P^{-}\phi(\vec{r};E)+\mathcal{O}(\nabla^2)$$

This work

In this work we have extended HAL metod to LS force.

LS force with parity minus sector in NN system is calculated.

Extension for LS force with S=1 system.

$$\left(\frac{\nabla^2}{m_N}+E\right)\phi^{(-)}(\vec{r};E)=\left[Vc^{(-)}(r)+V_T^{(-)}(r)S_{12}+V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S}\right]\phi^{(-)}(\vec{r};E)+\mathcal{O}(\nabla^2)$$

calculation of Vc , VT and VLS

parity minus , S=1 system:

$$\left(\frac{\nabla^2}{m_N}+E\right)\phi^{(-)}(\vec{r};E)=\left[Vc^{(-)}(r)+V_T^{(-)}(r)S_{12}+V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S}\right]\phi^{(-)}(\vec{r};E)+\mathcal{O}(\nabla^2)$$

$\phi^{(-)}(\vec{r})=\psi^{(1)}(\vec{r}),\ \psi^{(2)}(\vec{r}),\ \psi^{(3)}(\vec{r})$: linear independent each other

$$\left(\frac{\nabla^2}{2m}+E\right)\psi^{(1)}(\vec{r})=Vc^{(-)}\ \psi^{(1)}(\vec{r})+V_T^{(-)}S_{12}\ \psi^{(1)}(\vec{r})+V_{LS}^{(-)}\ \vec{L}\cdot\vec{S}\ \psi^{(1)}(\vec{r})$$

$$\left(\frac{\nabla^2}{2m}+E\right)\psi^{(2)}(\vec{r})=Vc^{(-)}\ \psi^{(2)}(\vec{r})+V_T^{(-)}S_{12}\ \psi^{(2)}(\vec{r})+V_{LS}^{(-)}\ \vec{L}\cdot\vec{S}\ \psi^{(2)}(\vec{r})$$

$$\left(\frac{\nabla^2}{2m}+E\right)\psi^{(3)}(\vec{r})=Vc^{(-)}\ \psi^{(3)}(\vec{r})+V_T^{(-)}S_{12}\ \psi^{(3)}(\vec{r})+V_{LS}^{(-)}\ \vec{L}\cdot\vec{S}\ \psi^{(3)}$$

NBS wave function $\psi^{(1)}(\vec{r}),\ \psi^{(2)}(\vec{r}),\ \psi^{(3)}(\vec{r})$ are calculated from Lattice QCD.

calculation of Vc , VT and VLS

$$\left(\frac{\nabla^2}{m_N}+E\right)\phi^{(-)}(\vec{r};E)=\left[Vc^{(-)}(r)+V_T^{(-)}(r)S_{12}+V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S}\right]\phi^{(-)}(\vec{r};E)+\mathcal{O}(\nabla^2)$$

Solve about Vc, VT, VLS

$$\begin{pmatrix}\left(\nabla^2/2m\right)\psi^{(1)}(\vec{r})\\ \left(\nabla^2/2m\right)\psi^{(2)}(r)\\ \left(\nabla^2/2m\right)\psi^{(3)}(\vec{r})\end{pmatrix}=\begin{pmatrix}\psi^{(1)}(\vec{r}) & S_{12}\ \psi^{(1)}(\vec{r}) & \vec{L}\cdot\vec{S}\ \psi^{(1)}(\vec{r})\\ \psi^{(2)}(\vec{r}), & S_{12}\ \psi^{(2)}(\vec{r}), & \vec{L}\cdot\vec{S}\ \psi^{(2)}(\vec{r}),\\ \psi^{(3)}(\vec{r}), & S_{12}\ \psi^{(3)}(\vec{r}), & \vec{L}\cdot\vec{S}\ \psi^{(3)}(\vec{r}),\end{pmatrix}\begin{pmatrix}Vc^{(-)}(r)-E\\ V_T^{(-)}(r)\\ V_{LS}^{(-)}(r)\end{pmatrix}$$

Vc, VT, VLS can be obtained from three wave function

$\psi^{(1)}(\vec{r}), \psi^{(2)}(\vec{r}), \psi^{(3)}(\vec{r})$

calculation of Vc , VT and VLS

$$\left(\frac{\nabla^2}{m_N}+E\right)\phi^{(-)}(\vec{r};E)=\left[Vc^{(-)}(r)+V_T^{(-)}(r)S_{12}+V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S}\right]\phi^{(-)}(\vec{r};E)+\mathcal{O}(\nabla^2)$$

Solve about Vc, VT, VLS

$$\begin{pmatrix} \psi^{(1)}(\vec{r}) & S_{12}\ \psi^{(1)}(\vec{r}) & \vec{L}\cdot\vec{S}\ \psi^{(1)}(\vec{r}) \\ \psi^{(2)}(\vec{r}), & S_{12}\ \psi^{(2)}(\vec{r}), & \vec{L}\cdot\vec{S}\ \psi^{(2)}(\vec{r}), \\ \psi^{(3)}(\vec{r}), & S_{12}\ \psi^{(3)}(\vec{r}), & \vec{L}\cdot\vec{S}\ \psi^{(3)}(\vec{r}), \end{pmatrix}^{-1} \begin{pmatrix} \left(\nabla^2/2m\right)\psi^{(1)}(\vec{r}) \\ \left(\nabla^2/2m\right)\psi^{(2)}(r) \\ \left(\nabla^2/2m\right)\psi^{(3)}(\vec{r}) \end{pmatrix} = \begin{pmatrix} Vc^{(-)}(r)-E \\ V_T^{(-)}(r) \\ V_{LS}^{(-)}(r) \end{pmatrix}$$

Vc, VT, VLS can be obtained from three wave function

$\psi^{(1)}(\vec{r}), \psi^{(2)}(\vec{r}), \psi^{(3)}(\vec{r})$

Here, $\psi^{(1)}(\vec{r}), \psi^{(2)}(\vec{r}), \psi^{(3)}(\vec{r})$ must be ....

- Parity Minus
- linear independent each other
- Orbit alangular momentum $L \neq 0$

$$\begin{pmatrix} \psi^{(1)}(\vec{r}) & S_{12}\ \psi^{(1)}(\vec{r}) & \vec{L}\cdot\vec{S}\ \psi^{(1)}(\vec{r}) \\ \psi^{(2)}(\vec{r}), & S_{12}\ \psi^{(2)}(\vec{r}), & \vec{L}\cdot\vec{S}\ \psi^{(2)}(\vec{r}), \\ \psi^{(3)}(\vec{r}), & S_{12}\ \psi^{(3)}(\vec{r}), & \vec{L}\cdot\vec{S}\ \psi^{(3)}(\vec{r}), \end{pmatrix}^{-1} \begin{pmatrix} \left(\nabla^2/2m\right)\psi^{(1)}(\vec{r}) \\ \left(\nabla^2/2m\right)\psi^{(2)}(r) \\ \left(\nabla^2/2m\right)\psi^{(3)}(\vec{r}) \end{pmatrix} = \begin{pmatrix} Vc^{(-)}(r) - E \\ V_T^{(-)}(r) \\ V_{LS}^{(-)}(r) \end{pmatrix}$$

Here, $\psi^{(1)}(\vec{r}), \psi^{(2)}(\vec{r}), \psi^{(3)}(\vec{r})$ must be ....

- Parity Minus
- linear independent each other
- Orbit alangular momentum $L \neq 0$

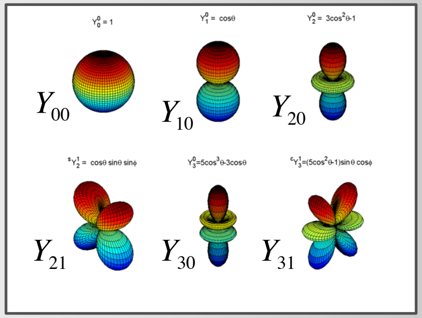
In this work, we calculated : ${}^3P_0$, ${}^3P_1$ and ${}^3P_2$

How to construct them ?

How to construct Parity odd, with $L \neq 0$

In previous works...

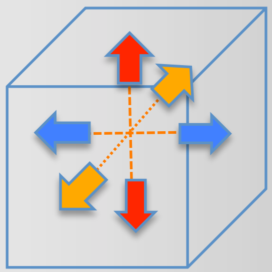
two nucleon in rest frame (wall sorce)



➡
- Parity Plus
- orbital angular momentum L=0

In this work :

- Impose the momentum to the nucleon (quark)
- construct the L=1 (on the cubic group : T1) state with combining 6-different direction of momentum.



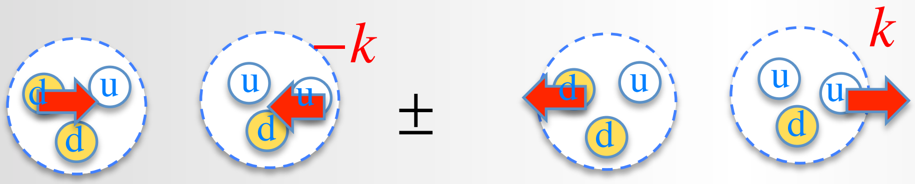
In this work, we calculated : ${}^3P_0$, ${}^3P_1$ and ${}^3P_2$

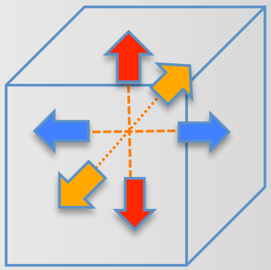
How to construct Parity odd state

Parity :

parity plus $$\phi(\vec{r})^{P=+} = \phi(\vec{r};+\vec{k}) + \phi(\vec{r};-\vec{k})$$

parity minus $$\phi(\vec{r})^{P=-} = \phi(\vec{r};+\vec{k}) - \phi(\vec{r};-\vec{k})$$



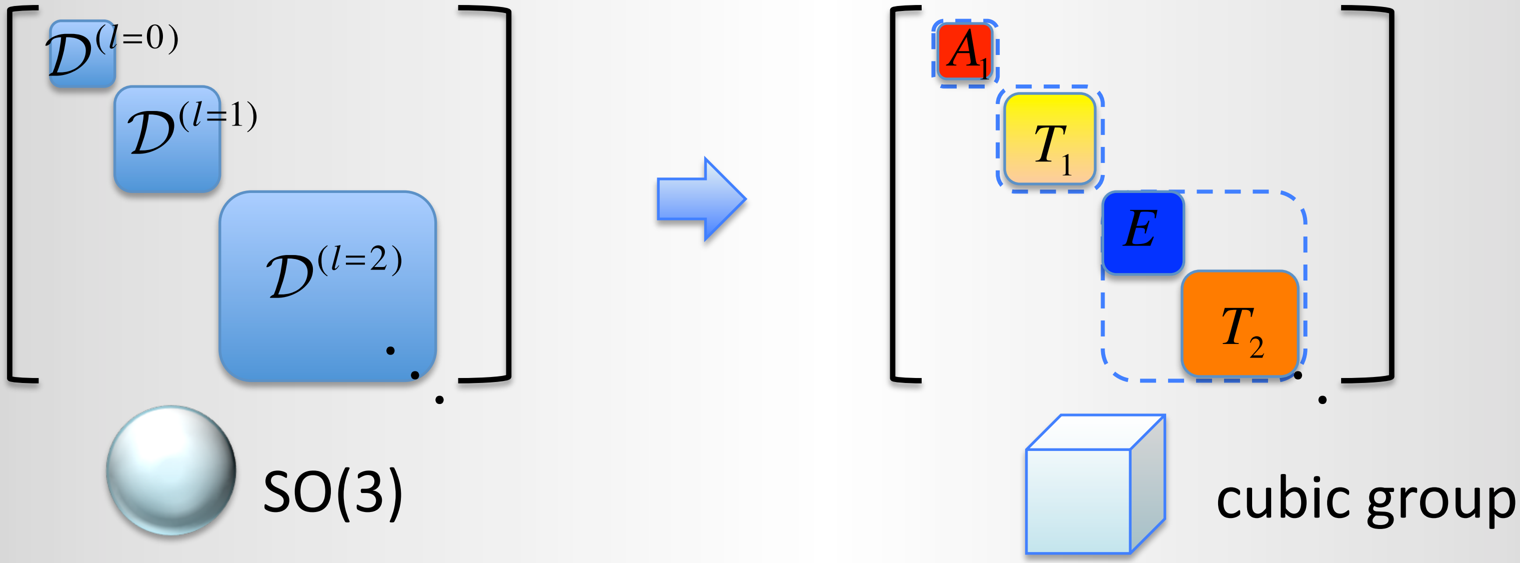


$$\bar{N}_\beta(f) \equiv \sum_{\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3} \varepsilon_{abc} \left(\bar{u}_a(\mathbf{x}_1) C\gamma_5 \bar{d}_b(\mathbf{x}_2)\right) \bar{d}_{c,\beta}(\mathbf{x}_3) . \exp(-i\vec{k}\cdot\vec{r})$$

- Impose the momentum to the nucleon (quark)
- subtracting NBS waves with opposite direction of momentum

How to construct $L \neq 0$ states

representation of SO(3) reduce to
"irreducible representation on the cubic group"



angular momentum, Spin → irreducible representation of cubic group

$$\not{L}, \not{S}, \not{J} \longrightarrow A_1, A_2, E, T_1, T_2$$

projection operator : in SO(3) case

An irreducible representation has an orthogonality (Group Orthogonality Theorem):

$$\int d\theta\, d\phi\; D^{(l)}_{\mu\nu}(\theta,\phi)^* D^{(l')}_{\mu'\nu'}(\theta,\phi) = \frac{4\pi}{2l+1}\delta_{l,l'}\delta_{\mu,\mu'}\delta_{\nu,\nu'}$$

We can extract definite angular momentum (representation on SO(3))

$$\psi(\vec{x}) = \psi^{(l=0)}(\vec{x}) + \psi^{(l=1)}(\vec{x}) + \cdots$$

$$\psi(R(\theta,\phi)\;\vec{x}) = D^{(l=0)}(\theta,\phi)\;\psi^{(l=0)}(\vec{x}) + D^{(l=1)}(\theta,\phi)\;\psi^{(l=1)}(\vec{x}) + \cdots$$

$$\Rightarrow \quad \frac{2l+1}{4\pi}\int d\theta\, d\phi\;\; D^{(l=L)}(\theta,\phi)^*\;\psi(R(\theta,\phi)\;\vec{x}) = \psi^{(l=L)}(\vec{x})$$

projection operator : in cubic group case

An irreducible representation has an orthogonality
(Group Orthogonality Theorem):

$$\sum_{i=0} D^{(\Gamma)}_{\mu\nu}(g_i)^* D^{(\Gamma')}_{\mu'\nu'}(g_i) = \frac{24}{d_\Gamma}\delta_{\Gamma,\Gamma'}\delta_{\mu,\mu'}\delta_{\nu,\nu'}, \quad \Gamma = A_1, A_2, E, T_1, T_2$$

In same way, we can extract definite representation on cubic group
(~ angular momentum)

$$\psi(\vec{x}) = \psi^{(A_1)}(\vec{x}) + \psi^{(A_2)}(\vec{x}) + \cdots$$

$$\psi(R(g_i)\ \vec{x}) = \mathcal{D}^{(A_1)}(g_i)\ \psi^{(A_1)}(\vec{x}) + D^{(A_2)}(g_i)\ \psi^{(A_2)}(\vec{x}) + \cdots$$

$$\Rightarrow \quad \frac{d_\Gamma}{24}\sum_{i=0}^{24} D^{(\Gamma)}_{\mu,\nu}(g_i)^* \psi_\nu(R(g_i)\ \vec{x}) = \psi^{(\Gamma)}_\mu(\vec{x})$$

projection operator : in cubic group case

An irreducible representation has an orthogonality (Group Orthogonality Theorem):

$$\sum_{i=0} D^{(\Gamma)}_{\mu\nu}(g_i)^* D^{(\Gamma')}_{\mu'\nu'}(g_i) = \frac{24}{d_\Gamma}\delta_{\Gamma,\Gamma'}\delta_{\mu,\mu'}\delta_{\nu,\nu'}, \quad \Gamma = A_1, A_2, E, T_1, T_2$$

In same way, we can extract definite representation on cubic group (~ angular momentum)

$$\psi(\vec{x}) = \psi^{(A_1)}(\vec{x}) + \psi^{(A_2)}(\vec{x}) + \cdots$$

$$\psi(R(g_i)\,\vec{x}) = D^{(A_1)}(g_i)\,\psi^{(A_1)}(\vec{x}) + D^{(A_2)}(g_i)\,\psi^{(A_2)}(\vec{x}) + \cdots$$

$$\Rightarrow \quad \frac{d_\Gamma}{24}\sum_{i=0}^{24}\chi(g_i)^*\psi(R(g_i)\,\vec{x}) = \psi^{(\Gamma)}(\vec{x}),$$

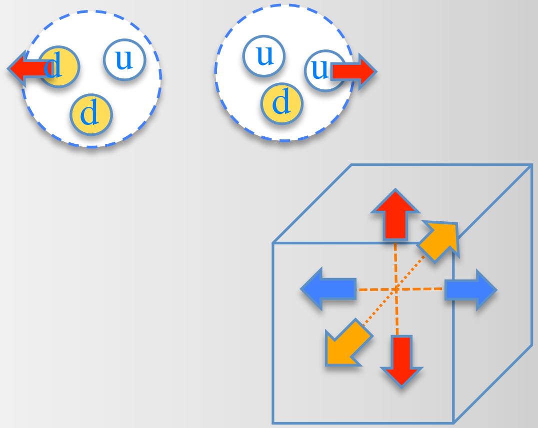
charcter $\chi = Tr\{D\}$

Construction of States

Parity :

parity plus $\phi(\vec{r})^{P=+} = \phi(\vec{r};+\vec{k}) + \phi(\vec{r};-\vec{k})$

parity minus $\phi(\vec{r})^{P=-} = \phi(\vec{r};+\vec{k}) - \phi(\vec{r};-\vec{k})$



we impose momentum to nucleus

Angular momentum:

Projection operator
based on cubic group:
because rotational sym
is broken O(3) ➔ cubic group

$$\frac{2l+1}{4\pi}\int d\theta\, d\phi \;\; D^{(l=L)}(\theta,\phi)^{*}\;\psi(R(\theta,\phi)\;\vec{x})$$

$$\frac{d_\Gamma}{24}\sum_{i=0}^{24} D^{(\Gamma)}_{\mu,\nu}(g_i)^{*}\psi_\nu(R(g_i)\;\vec{x})$$

Great Orthogonally : $\sum_{i=0} D^{(\Gamma)}_{\mu\nu}(g_i)^{*} D^{(\Gamma')}_{\mu'\nu'}(g_i) = \frac{24}{d_\Gamma}\delta_{\Gamma,\Gamma'}\delta_{\mu,\mu'}\delta_{\nu,\nu'},\quad \Gamma = A_1, A_2, E, T_1, T_2$

Numerical Results

Set Up

Japan Lattice Data Grid

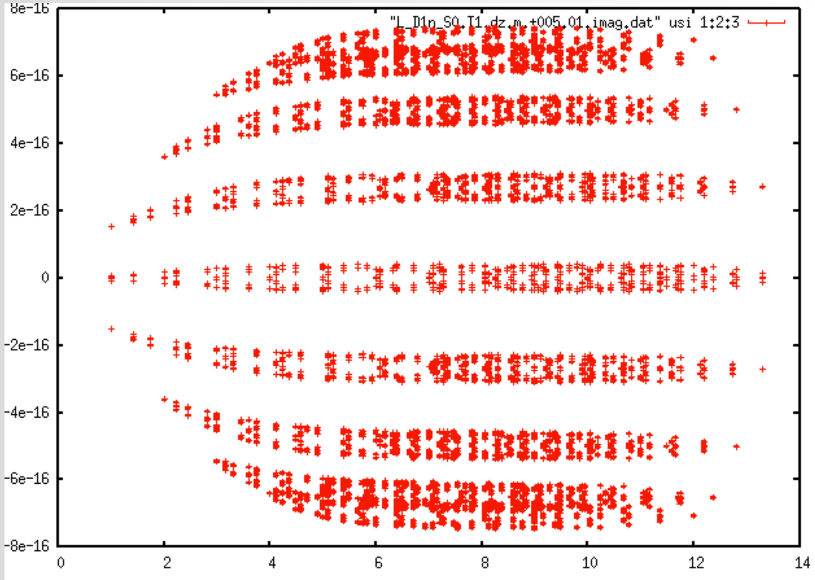
Nf=2
Iwasaki gauge + clover fermion
beta=0.195
kappa=0.1375

a=0.1555
1/a = 1271 MeV
L^3 x T = 16 ^3 x 32
mN=2165 MeV
mpi=1136 MeV

heavy quark mass
(calculation cost ∝ 1/mq)

spin-singlet (S=0)
parity minus

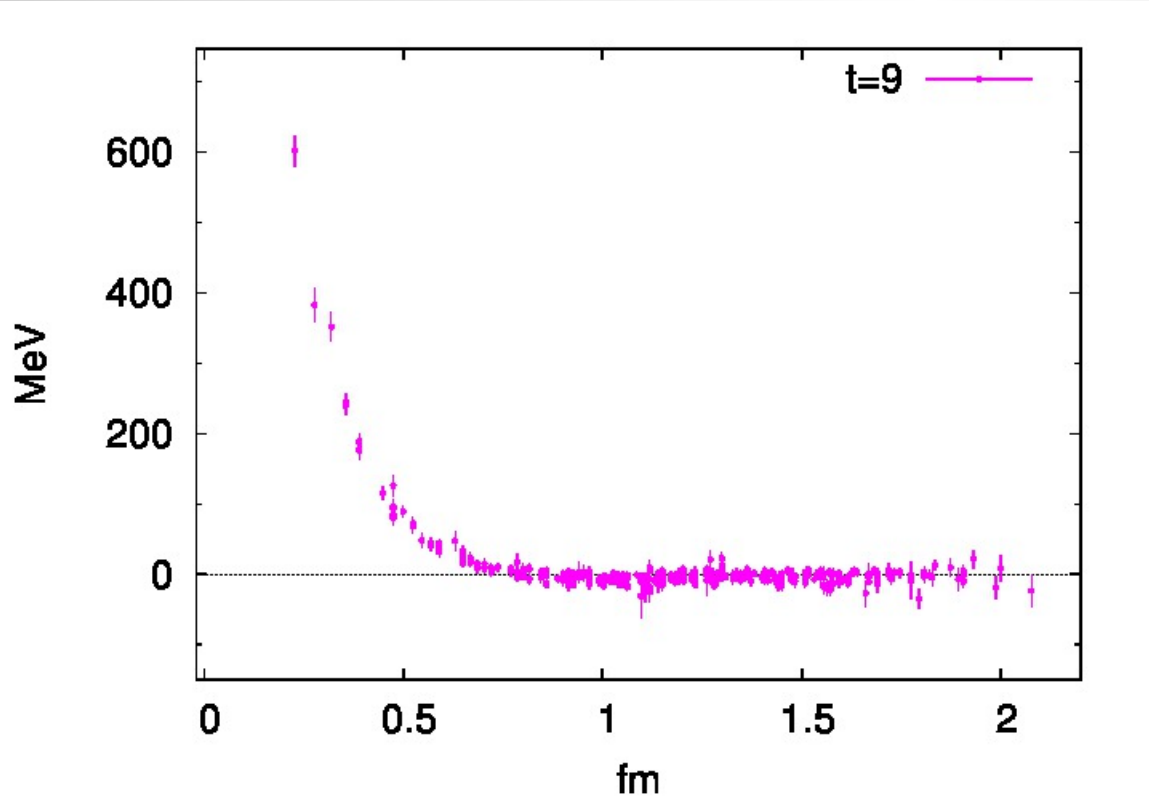
1P1 NBS wave function for S=0



$$\left(\frac{\nabla^2}{m_N}+E\right)\phi^{(-)}(\vec{r};E)=\left[Vc^{(-)}(r)+V_T^{(+)}(r)S_{12}+V_{LS}^{(+)}(r)\vec{L}\cdot\vec{S}\right]\phi^{(-)}(\vec{r};E)$$

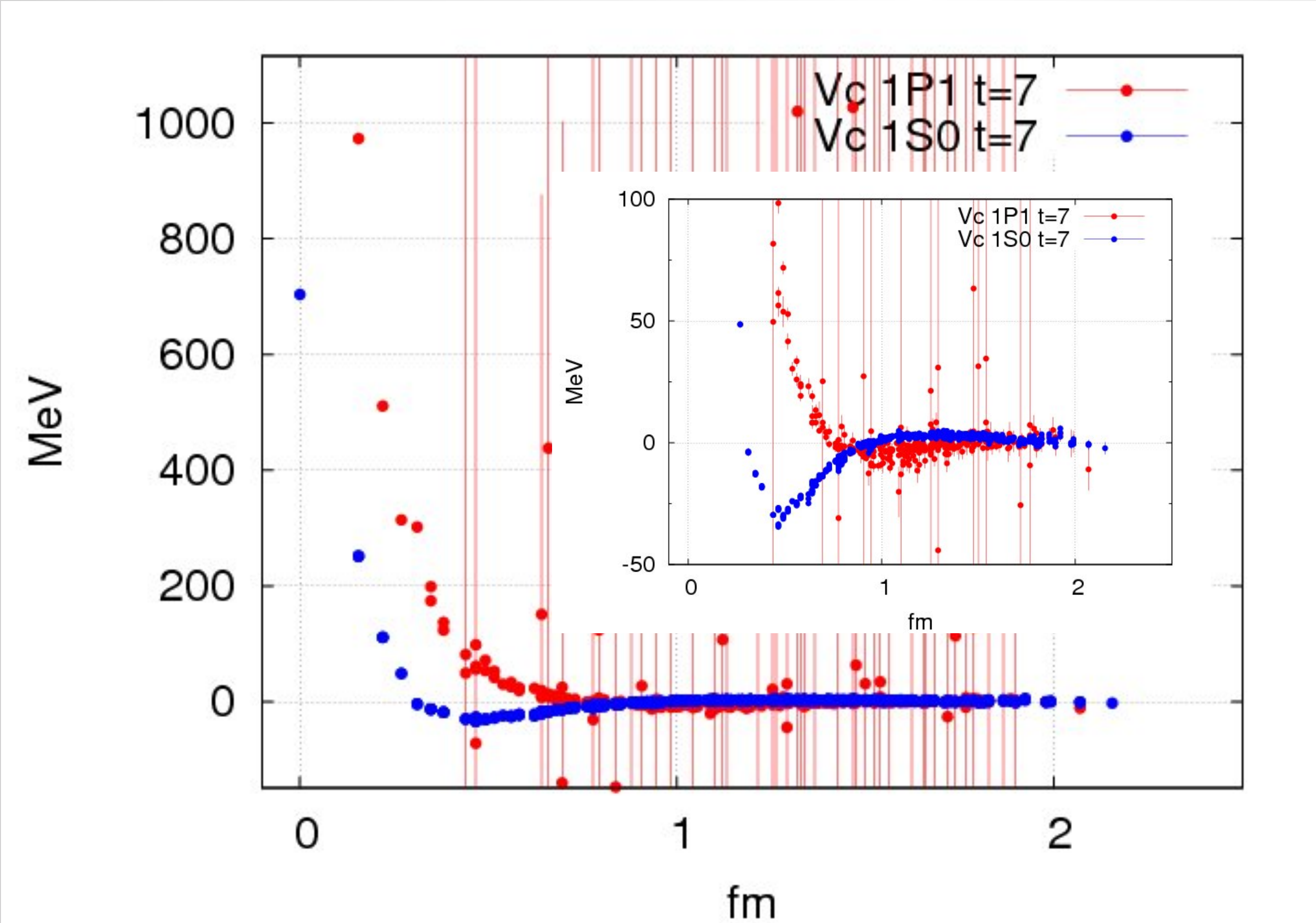
$$\Rightarrow Vc_{S=0}^{(-)}(r)=\left(\frac{1}{m_N}\frac{\Delta\phi(r;E)}{\phi(r;E)}+E\right)$$

1P1 (S=0) central potential for parity odd



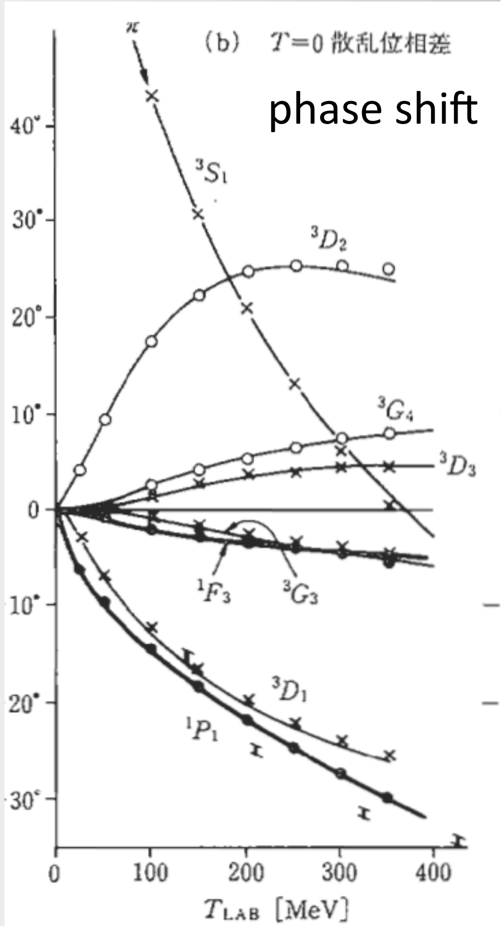
(so3 improved ver, not time-dependent)

- comparison of central potential in parity even and one in parity odd.



Parity Plus

Parity Minus



- parity odd central force (from 1P1) has strong repulsive core

1P1 cos type source ･･ $E=(2\pi/L)^2/m_N$

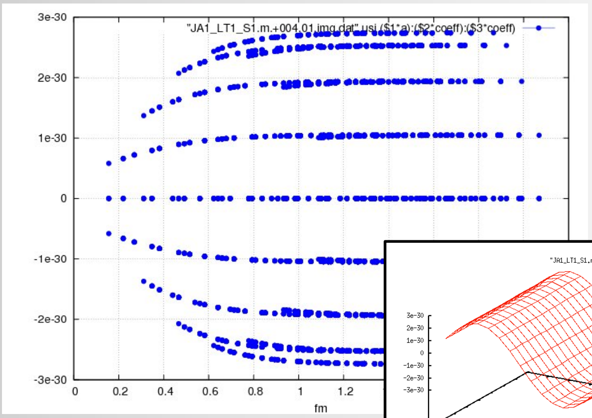
1S0 wall source ･･ shift

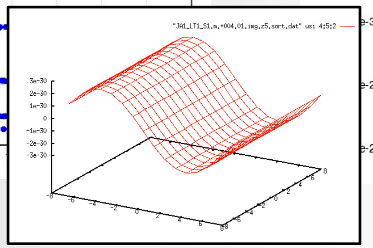
spin-triplet (S=1)
parity minus

results : NBS wave function for S=1

3P0

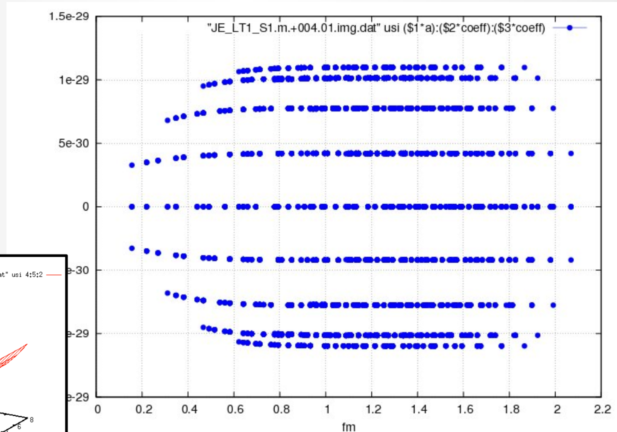
J=1 (A1) L=1 (T1) (imaginary part)





3P2

J=2 (E) L=1 (T1) (imaginary part)

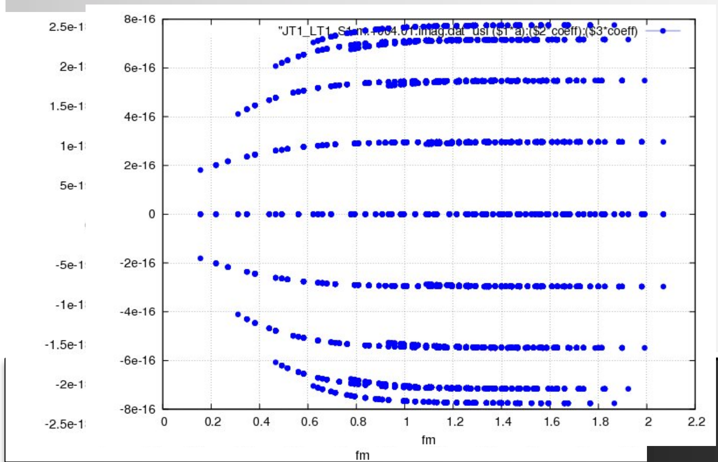


a=0.1555
1/a = 1271 MeV
L^3 x T = 16 ^3 x 32
mN=2165 MeV

$$\psi(\vec{r}) = R(r)Y_{1m}(\theta,\phi)$$

3P1

J=1 (T1) L=1 (T1)



We have obtained

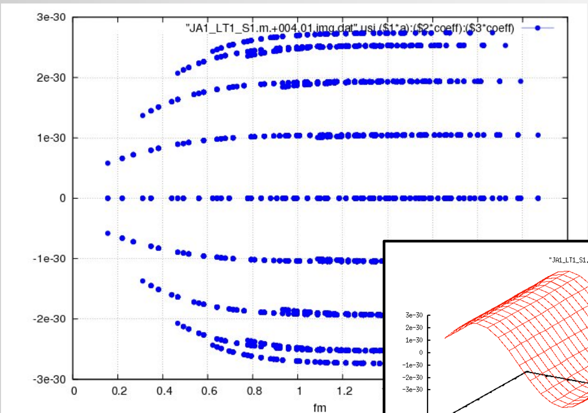
3P0, 3P1, 3P2, 3F2, 3F3

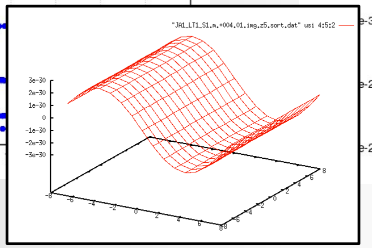
NBS wave functions

results : NBS wave function for S=1

3P0

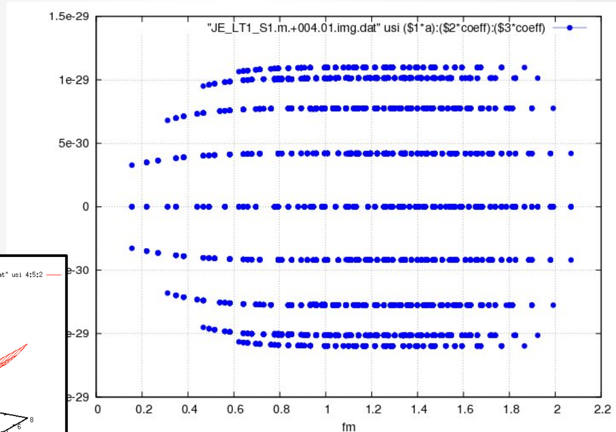
J=1 (A1) L=1 (T1) (imaginary part)





3P2

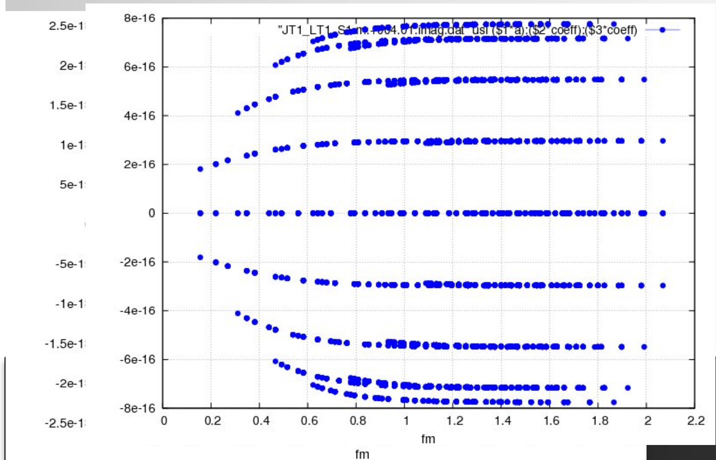
J=2 (E) L=1 (T1) (imaginary part)



a=0.1555
1/a = 1271 MeV
L^3 x T = 16 ^3 x 32
mN=2165 MeV

3P1

J=1 (T1) L=1 (T1)

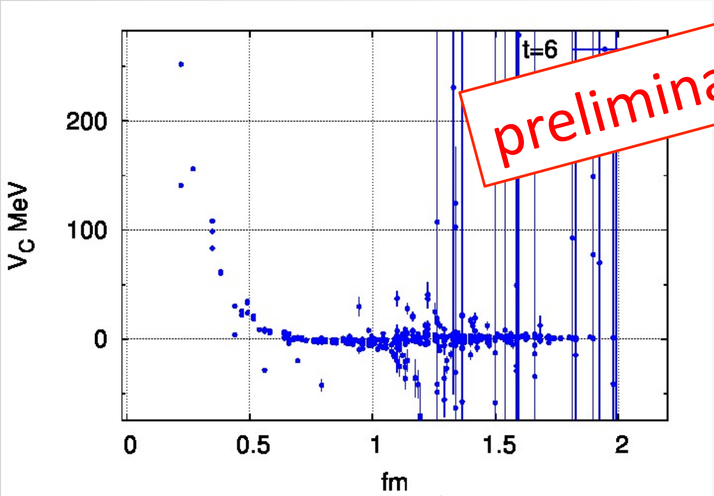


$$\psi(\vec{r}) = R(r) Y_{1m}(\theta,\phi)$$

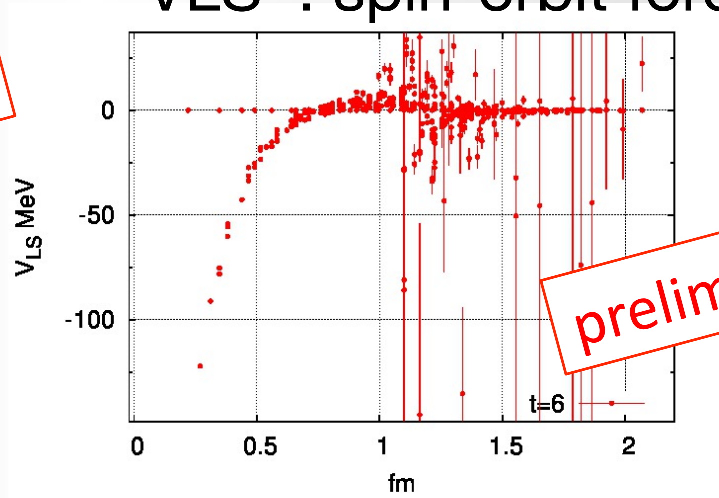
$$\begin{pmatrix} (\nabla^2/2m)\, {}^3P_0(\vec{r}) \\ (\nabla^2/2m)\, {}^3P_1(r) \\ (\nabla^2/2m)\, {}^3P_2(\vec{r}) \end{pmatrix} = \begin{pmatrix} {}^3P_0(\vec{r}) & S_{12}\, {}^3P_0(\vec{r}) & \vec{L}\cdot\vec{S}\, {}^3P_0(\vec{r}) \\ {}^3P_1(\vec{r}), & S_{12}\, {}^3P_1(\vec{r}), & \vec{L}\cdot\vec{S}\, {}^3P_1(\vec{r}), \\ {}^3P_2(\vec{r}), & S_{12}\, {}^3P_2(\vec{r}), & \vec{L}\cdot\vec{S}\, {}^3P_2(\vec{r}), \end{pmatrix} \begin{pmatrix} Vc^{(-)}(r) - E \\ V_T^{(-)}(r) \\ V_{LS}^{(-)}(r) \end{pmatrix}$$

Numerical results of potentials S=1 parity minus

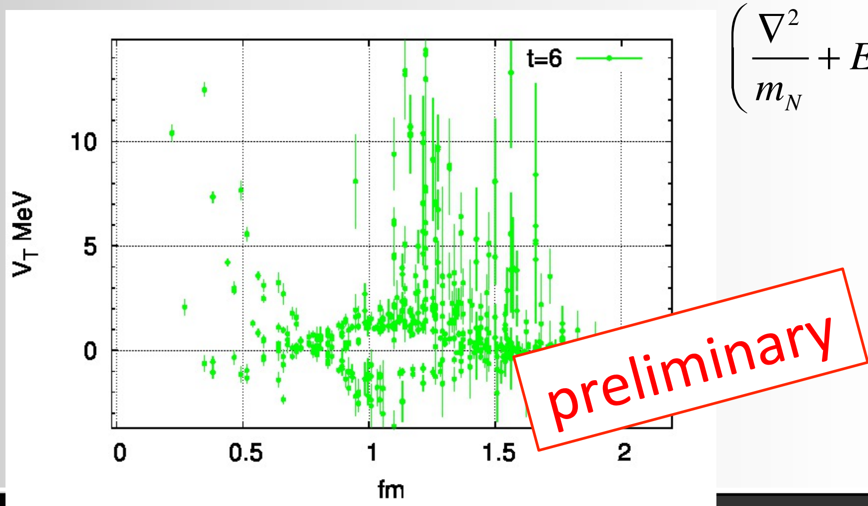
Vc : center force



VLS : spin-orbit force



VT : tensor force

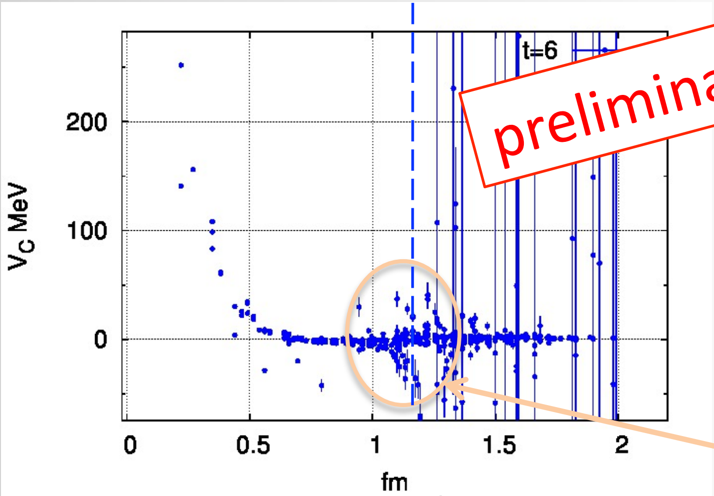


$$\left(\frac{\nabla^2}{m_N}+E\right)\phi(\vec{r};E)=\left[Vc^{(+)}(r)+V_T^{(+)}(r)S_{12}+V_{LS}^{(+)}(r)\vec{L}\cdot\vec{S}\right]P^{+}\phi(\vec{r};E)$$

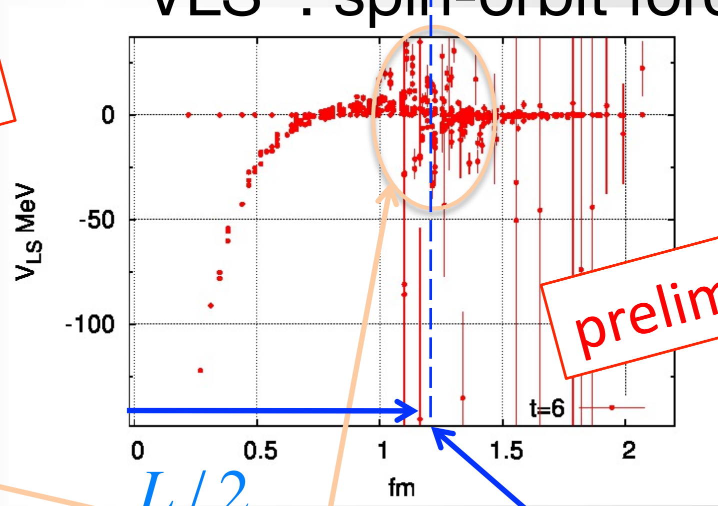
$$+\left[Vc^{(-)}(r)+V_T^{(-)}(r)S_{12}+V_{LS}^{(-)}(r)\vec{L}\cdot\vec{S}\right]P^{-}\phi(\vec{r};E)+\mathcal{O}(\nabla^2)$$

Numerical results of potentials S=1 parity minus

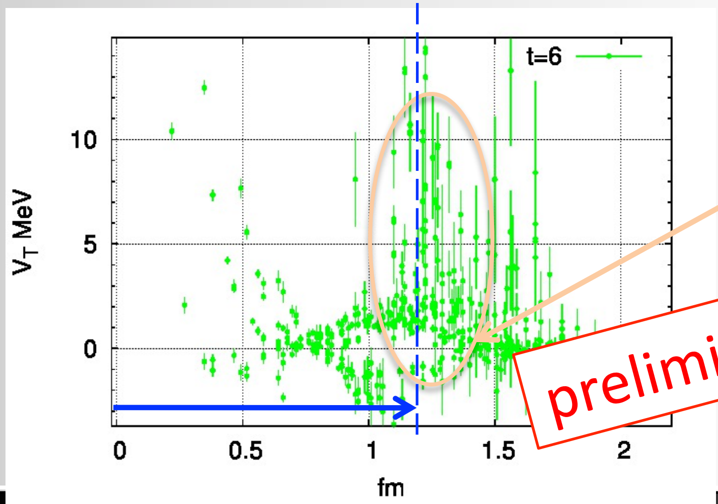
Vc : center force



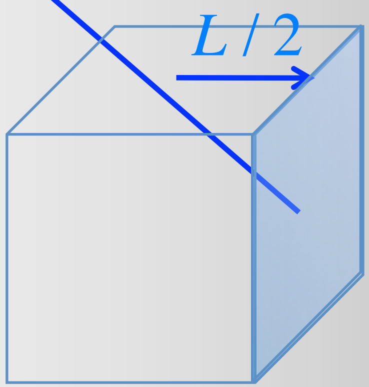
VLS : spin-orbit force



VT : tensor force



there are strong fluctuation.



← caused by boundary.

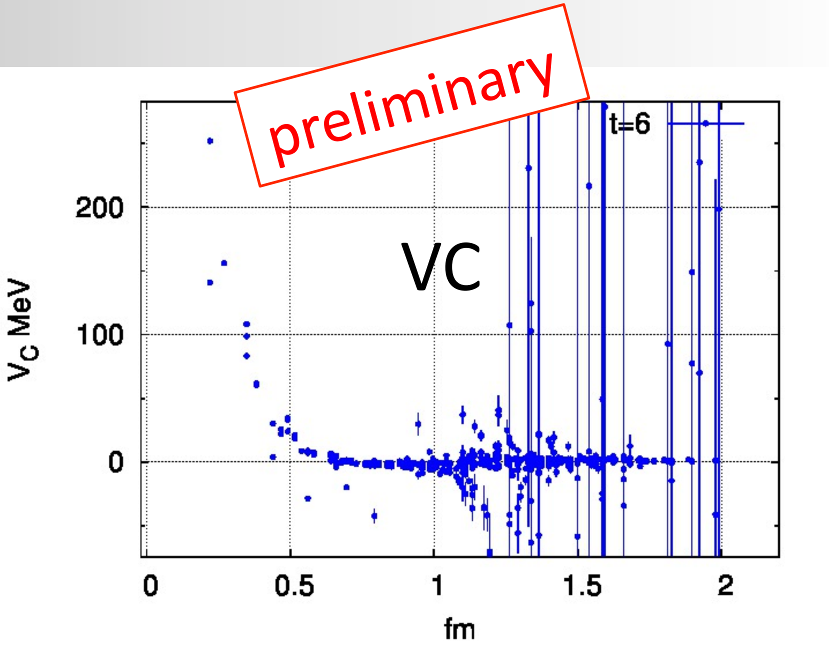
NBS wave has strong finite effect

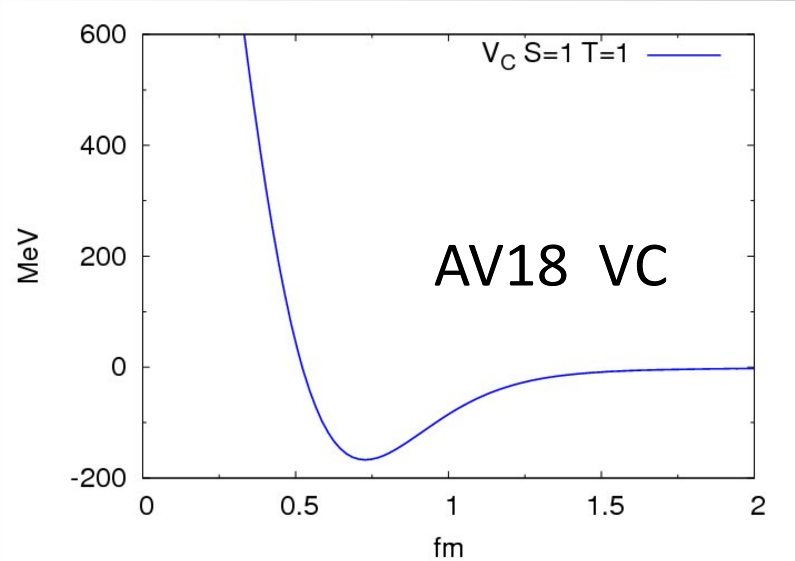
comparison with phenomenological potential (AV18)

central force has repulsive core
(qualitatively same with one with AV18)

Phys. Rev. C **51**, 38 (1995)

R. B. Wiringa, V. G. J. Stoks and R.Schiavilla,



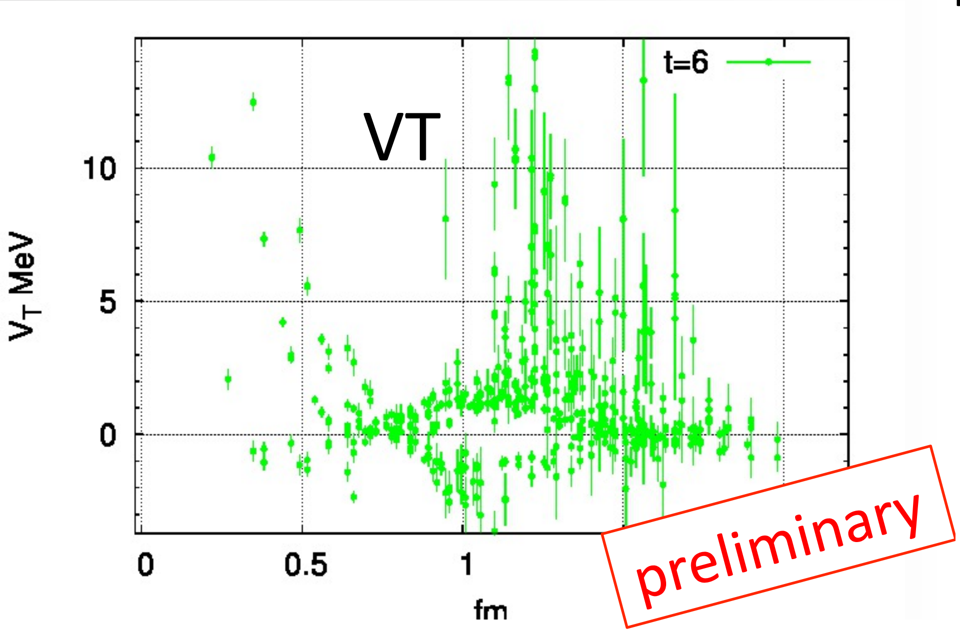


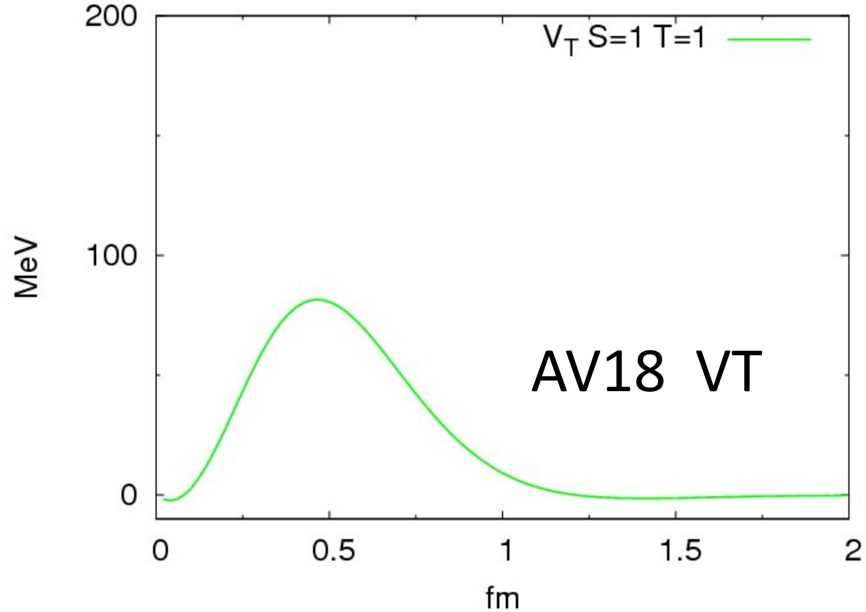
$$v^{R}_{ST}(NN) = v^{c}_{ST,NN}(r) + v^{l2}_{ST,NN}(r)L^2 + v^{t}_{ST,NN}(r)S_{12} + v^{ls}_{ST,NN}(r)\mathbf{L}\cdot\mathbf{S} + v^{ls2}_{ST,NN}(r)(\mathbf{L}\cdot\mathbf{S})^2$$

comparison with phenomenological potential (AV18)

tensor force is weak repulsive force
(qualitatively same with one with AV18)

Phys. Rev. C **51**, 38 (1995)
R. B. Wiringa, V. G. J. Stoks and R.Schiavilla,





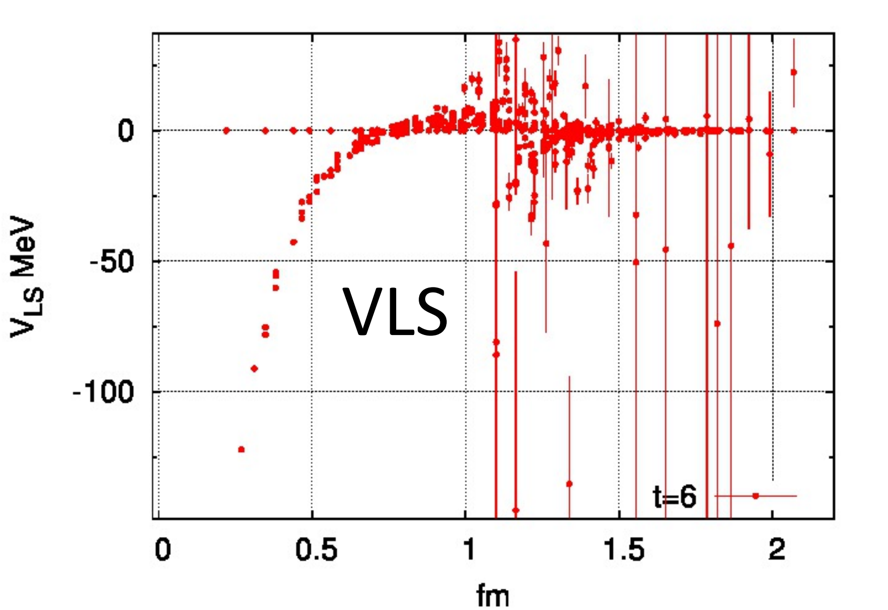
$$v^R_{ST}(NN) = v^c_{ST,NN}(r) + v^{l2}_{ST,NN}(r)L^2 + v^t_{ST,NN}(r)S_{12} + v^{ls}_{ST,NN}(r)\mathbf{L}\cdot\mathbf{S} + v^{ls2}_{ST,NN}(r)(\mathbf{L}\cdot\mathbf{S})^2$$

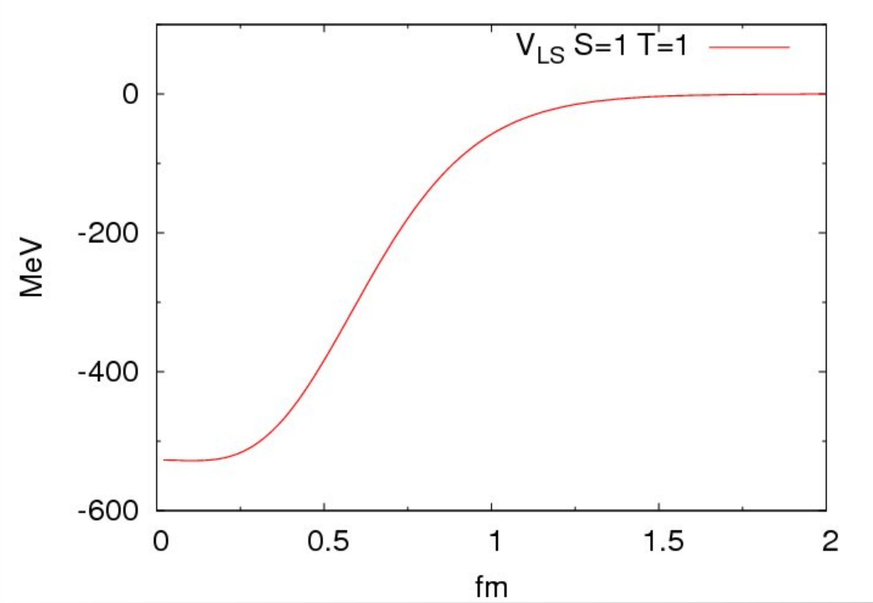
comparison with phenomenological potential (AV18)

LS force is strong attractive force
(qualitatively same with one with AV18)

Phys. Rev. C **51**, 38 (1995)

R. B. Wiringa, V. G. J. Stoks and R.Schiavilla,

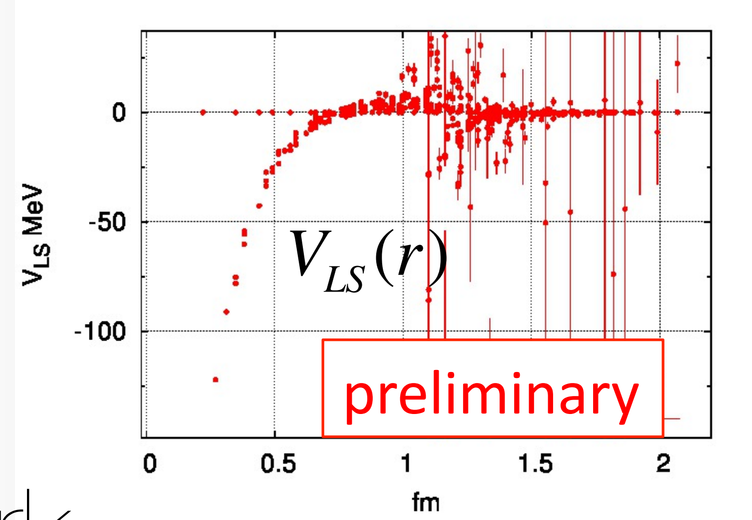




$$v^R_{ST}(NN) = v^c_{ST,NN}(r) + v^{l2}_{ST,NN}(r)L^2 + v^t_{ST,NN}(r)S_{12} + \boxed{v^{ls}_{ST,NN}(r)}\,\mathbf{L}\cdot\mathbf{S} + v^{ls2}_{ST,NN}(r)(\mathbf{L}\cdot\mathbf{S})^2$$

Summary

We are currently preparing the calculation of potentials including LS forces for parity minus sector.



Future work

- parity plus LS force

- physical point (mpi = 135 MeV)
- applied for YN and YY interaction

will be performed in K-Computer (2012).