Hyperon-deuteron momentum correlation function including the effect of the deuteron breakup

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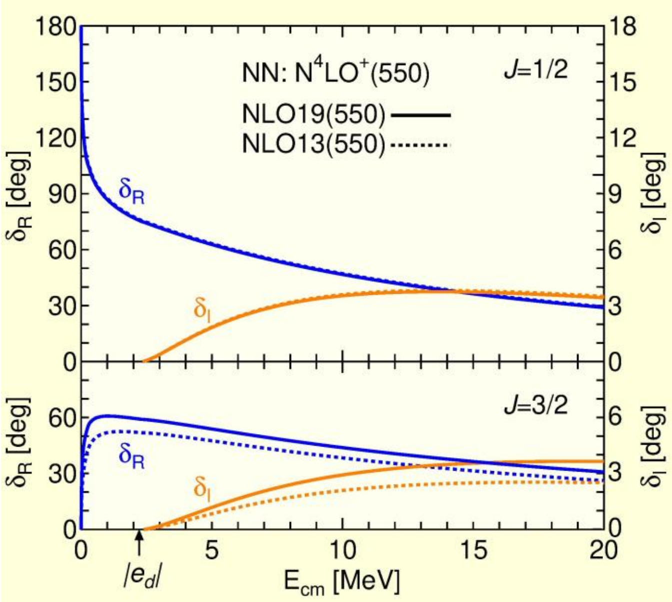
- Understanding of hyperon-nucleon interactions remains in its infancy due to the paucity of experimental data.
  - Direct Λ-nucleon scattering experiments are currently in the planning stages.
- Correlation functions measured in heavy-ion collisions are identified as a potential source of information.
- This talk discusses the effects of the deuteron breakup, occurring in both the incident and rearrangement channels, on the Λ-deuteron correlation function.
  - *Λnp* three-body wave functions are calculated using Faddeev amplitudes.

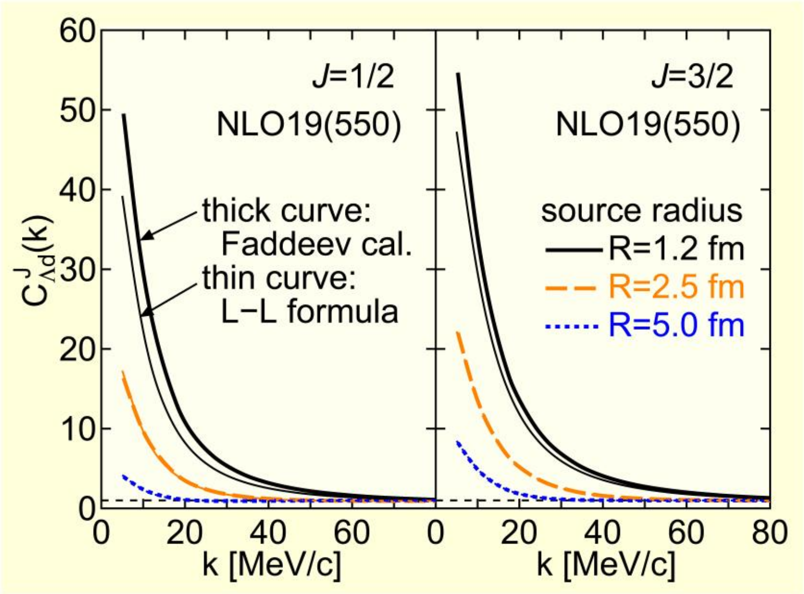
Faddeev calculations of low-energy Λ-*d* phase shifts and correlation functions

- We have described Λ-deuteron scattering in a Faddeev formulation using ChEFT NN and YN interactions.
  - Correlation functions employing the Λ-*d* elastic wave functions were reported in **"Faddeev calculations of low-energy Λ-deuteron scattering and momentum correlation function"**, M. Kohno and H. Kamada, Phys. Rev. C110, 044005 (2024).



- The difference in the phase shifts between NLO13 and NLO19 shows the properties of these interactions.

- The Lednicky-Lyuboshits formula works well for a source radius $R > 2.5$ fm.



- Modification of the deuteron wave function was taken care of, but the deuteron breakup was not.

Correlation function $R(q)$ (S. Mrówozyński [Eur. Phys. J. Spec. Top. 229, 3559(2020)])

$$R(q) = \iiint d\boldsymbol{r}_\Lambda d\boldsymbol{r}_n d\boldsymbol{r}_p\, D(r_\Lambda)D(r_n)D(r_p)|\psi_{\Lambda np}(\boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np})|^2 \Big/ \iint d\boldsymbol{r}_n d\boldsymbol{r}_p\, D(r_n)D(r_p)|\varphi_d(\boldsymbol{r}_{np})|^2$$

source function $D(r) = D(r; R_s) \equiv (\sqrt{2\pi}R_s)^{-3} e^{-r^2/(2R_S^2)}$, $\psi_{\Lambda np}(\boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}) \xrightarrow[|\boldsymbol{r}_{\Lambda(np)}|, |\boldsymbol{r}_{np}| \to \infty]{} e^{i\boldsymbol{q}_0 \cdot \boldsymbol{r}_{\Lambda(np)}} \psi_d(\boldsymbol{r}_{np})$

- The cm coordinate is integrated out.

$$R(q) = \iint d\boldsymbol{r}_{\Lambda(np)} d\boldsymbol{r}_{np}\, D\left(r_{\Lambda(np)}; \sqrt{3/2}R_s\right) D\left(r_n; \sqrt{2}R_s\right) |\psi_{\Lambda np}(\boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np})|^2 \Big/ \int d\boldsymbol{r}_{np}\, D\left(r_{np}; \sqrt{2}R_s\right)|\varphi_d(\boldsymbol{r}_{np})|^2$$

  - Supposing the deuteron is an elementary particle $\psi_{\Lambda np}(\boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}) = \psi_{\Lambda d}(\boldsymbol{r}_{\Lambda\mathrm{d}})\varphi_d(\boldsymbol{r}_{np})$,

$$R(q) = \int d\boldsymbol{r}_{\Lambda d} D\left(r_{\Lambda d}; \sqrt{3/2}R_s\right) |\psi_{\Lambda d}(\boldsymbol{r}_{\Lambda\mathrm{d}})|^2$$ (note that the range is $\sqrt{3/2}R_s$ instead of $\sqrt{2}R_s$)

  - Assuming the Λd relative wave function differs from the plane $e^{i\boldsymbol{q}_0 \cdot \boldsymbol{r}_{\Lambda d}}$ only in the s wave,

$$R(q) \cong 1 + 4\pi \int r_{\Lambda d}^2 dr_{\Lambda d}\, D\left(r_{\Lambda d}; \sqrt{3/2}R_s\right) \left\{|\psi_{\Lambda d}^{l=0}(r_{\Lambda\mathrm{d}})|^2 - |j_0(r_{\Lambda d})|^2\right\}$$

  - When $\psi_{\Lambda d}^{l=0}(r_{\Lambda\mathrm{d}})$ is described by effective range parameters, L-L formula is obtained.

- We do not use the factorization approximation: $\psi_{\Lambda np}(\boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}) \neq \psi_{\Lambda d}(\boldsymbol{r}_{\Lambda\mathrm{d}})\varphi_d(\boldsymbol{r}_{np})$.

Correlation function $R(q)$ （S. Mrówozyńsky [Eur. Phys. J. Spec. Top. 229, 3559(2020)]）

- In the case of $\psi_{\Lambda np}(\boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}) \neq \psi_{\Lambda d}(\boldsymbol{r}_{\Lambda\mathrm{d}})\varphi_d(\boldsymbol{r}_{np})$

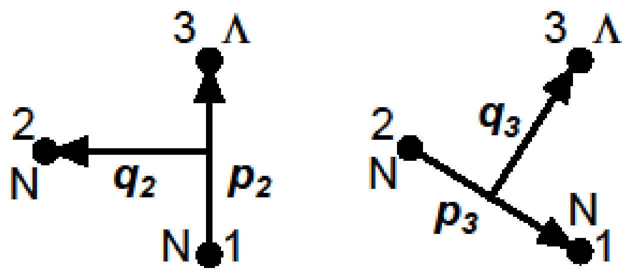
$$R(q) = \iint d\boldsymbol{r}_{\Lambda(np)} d\boldsymbol{r}_{np}\, D\left(r_{\Lambda(np)}; \sqrt{3/2}R_s\right) D\left(r_n; \sqrt{2}R_s\right) |\psi_{\Lambda np}(\boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np})|^2 \Big/ \int d\boldsymbol{r}_{np}\, D\left(r_{np}; \sqrt{2}R_s\right) |\varphi_d(\boldsymbol{r}_{np})|^2$$

- Assuming that only the s-wave is altered from the plane wave $e^{i\boldsymbol{q}_0 \cdot \boldsymbol{r}_{\Lambda d}}$

$$R(q) \times \int d\boldsymbol{r}_{np}\, D\left(r_{np}; \sqrt{2}R_s\right) |\varphi_d(\boldsymbol{r}_{np})|^2$$

$$\cong 1 + (4\pi)^2 \iint r_{\Lambda d}^2 dr_{\Lambda d} r_{np}^2 dr_{np}\, D\left(r_{\Lambda d}; \sqrt{3/2}R_s\right) D\left(r_{np}; \sqrt{2}R_s\right) \left(|\psi_{\Lambda np}^{l=0}(r_{\Lambda d}, r_{np})|^2 - |j_0(r_{\Lambda d})|^2 |\varphi_d(\boldsymbol{r}_{np})|^2\right)$$

- $\psi_{\Lambda np}^{l=0}(r_{\Lambda d}, r_{np})$ is constructed from Faddeev amplitudes.
  - Incident-channel wave function
  - Full three-body wave function including the breakup in the rearrangement channel



Wave function in the incident channel

- Λd incident channel: $\langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np} | \Psi_3^{(+)} \rangle = \langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np} | \phi \rangle + \langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np} | G_3 | \phi_0 \rangle \langle \phi_0 | 2T_2 | \phi \rangle$
  - channel Green function $G_3 = \frac{1}{E - H_0 - V_{12}}$ $(V_{12} = V_{np})$

    $\langle \phi_0 |$ is the plane wave basis.
    The definition of $T_2 | \phi \rangle$ is on the next slide.
  - To explicitly evaluate $\langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np} | G_3 | \phi_0 \rangle$, the eigen functions $| \Phi \rangle$ of $H_0 + V_{12}$ are used.

    $\Rightarrow \langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np} | G_3 | \Phi \rangle \langle \Phi | \phi_0 \rangle$

- Spectral representation of the Green function (s-wave) [$| \Phi \rangle \langle \Phi | = | \Phi_d \rangle \langle \Phi_d | + | \Phi_{scat} \rangle \langle \Phi_{scat} |$]

$$\langle r_{\Lambda(np)}, r_{np} | G_3 | \Phi_d , \Phi_{scat} \rangle * = \int q^2 dq \frac{\varphi_d(r_{np}) j_o(q r_{\Lambda(np)})}{E + |e_d| - \frac{\hbar^2}{2\mu_{\Lambda np}} q^2 + i\mathcal{E}} * , \quad \frac{2}{\pi} \iint p^2 dp\, q^2 dq \frac{\psi_p(r_{np}) j_o(q r_{\Lambda(np)})}{E - \frac{\hbar^2}{2\mu_{np}} p^2 - \frac{\hbar^2}{2\mu_{\Lambda np}} q^2 + i\mathcal{E}} *$$

  - $\varphi_d(r_{np})$ and $\psi_p(r_{np})$: bound state and scattering state wave functions of $T_3 + V_{12}$
  - Φ_d term indicates the elastic scattering, and the second term breakup in the incident channel

Full three-body wave function in Faddeev formulation

- The breakup in the rearrangement channel is included in the full three-body wave function:

$$\Psi^{(+)} = \lim_{\varepsilon\to 0} i\varepsilon \frac{1}{E+i\varepsilon-H}\phi = \Psi_1^{(+)} + \Psi_2^{(+)} + \Psi_3^{(+)}, \qquad [H = H_0 + V_{12} + V_{23} + V_{31}, \phi \text{ is incident wave}]$$

- Rewriting $(H_0 + V_1 + V_2 + V_3 - E)\Psi^{(+)} = 0$ to $\Psi^{(+)} = G_0(V_1 + V_2 + V_3)\Psi^{(+)}$ $\left[G_0 = \frac{1}{E-H_0}\right]$

- $u_3|\phi\rangle \equiv (V_{31} + V_{23})|\Psi^{(+)}\rangle$ and introducing two-body t-matrix t_i ($i = 3$ is assigned to Λ)

  Faddeev equation becomes $u_3\phi = (1 - P_{12})t_2 G_0 u_2\phi$, $u_2\phi = G_0^{-1}\phi + t_3 G_0 u_3\phi - P_{12}t_2 G_0 u_2\phi$

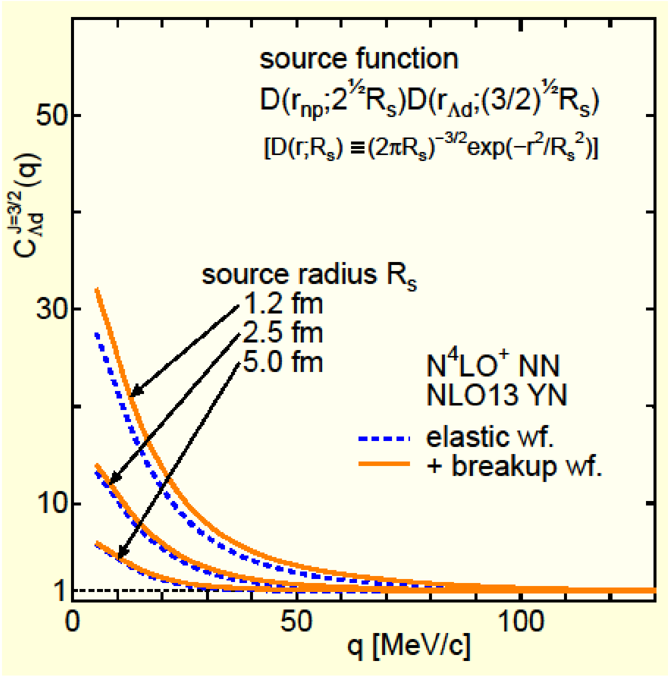
  Introducing $T_i \equiv t_i G_0 u_i$, then $T_3\phi = t_3 G_0(1 - P_{12})T_2\phi, \quad T_2\phi = t_2\phi + t_2 G_0 T_3\phi - t_2 P_{12} G_0 T_2\phi$

- Inserting complete set of the plane wave $|\phi_0\rangle\langle\phi_0| = 1$, the wave function is written as

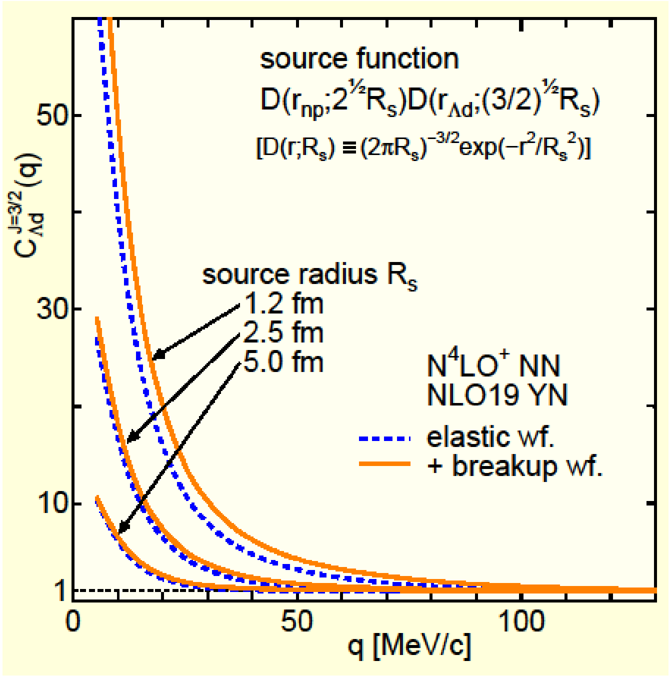
$$\begin{aligned}\langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}|\Psi^{(+)}\rangle &= \langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}|G_0|\phi_0\rangle\langle\phi_0|V_{12} + V_{23} + V_{31}|\Psi^{(+)}\rangle \\ &= \langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}|G_0|\phi_0\rangle\langle\phi_0|G_0^{-1} + 2T_2 + T_3|\phi\rangle \\ &= \langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}|\phi\rangle + \langle \boldsymbol{r}_{\Lambda(np)}, \boldsymbol{r}_{np}|G_0|\phi_0\rangle\langle\phi_0|2T_2 + T_3|\phi\rangle\end{aligned}$$

Contributions of deuteron breakup processes to Λ-d correlation functions

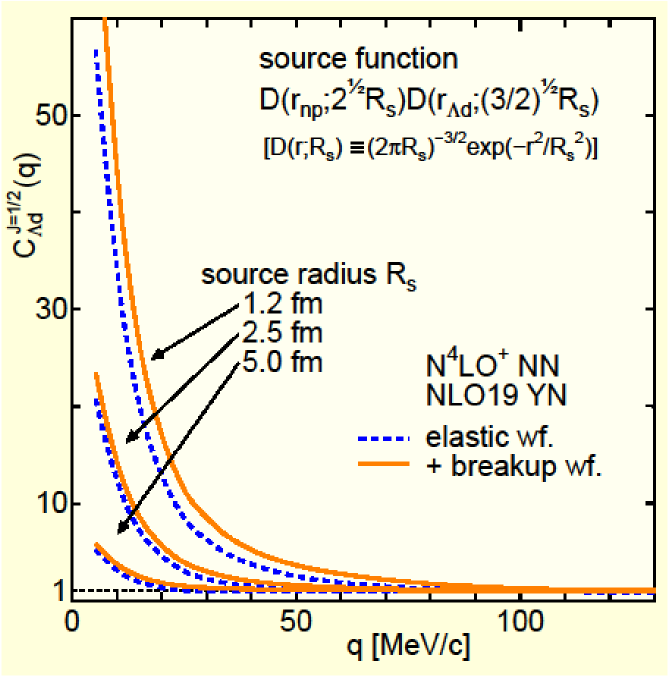
- Using three-body wave functions calculated from Faddeev amplitudes
  - Contributions of the Incident channel breakup are negligible.
  - Contributions of the rearrangement channel breakup are not negligible, but small for $R < 2.5$ fm.



J=3/2 with NLO13 YN



J=3/2 with NLO19 YN



J=1/2 with NLO19 YN

Summary

- The contributions of the deuteron breakup processes to the Λ-d correlation functions are calculated using the wave functions in the Faddeev formulation.
  - The deuteron breakup in the incident channel yields a negligible effect on the Λ-d correlation function.
  - The contribution from the rearrangement channel breakup provides a certain enhancement.
  - Absent the consideration of the breakup effects, the source radius is somewhat underestimated.

- The next subject is the correlation functions between another hyperon and deuteron.
  - The effects of the deuteron breakup are expected to be more pronounced in the Ξ-d correlation function because the $^1S_0$ can contribute.