Prospects for studying the structure of unbound nuclei in (d, p) reactions

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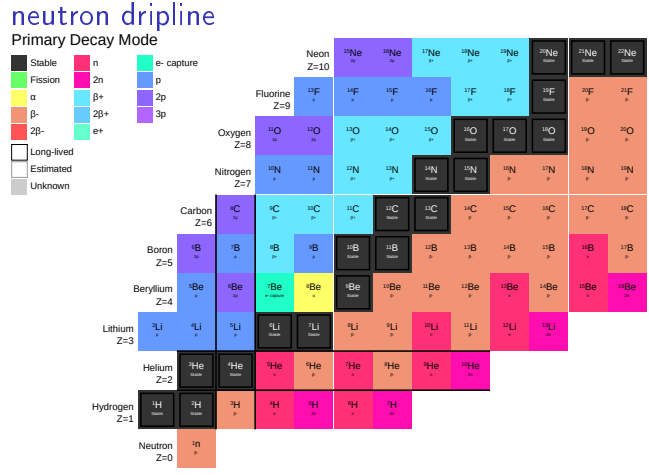
Nuclear systems near drip-line

- The lightest nuclides near dripline have been studied for decades.
- There are no consistent conclusions about their structure
- Additional experimental studies are required...

Outline:

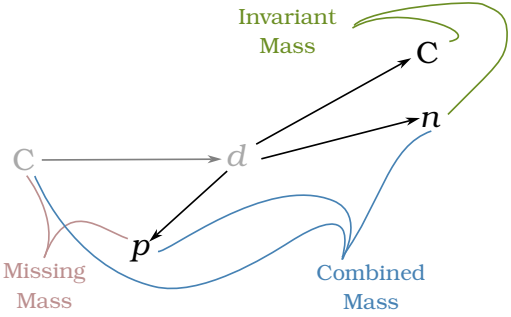
- (d, p) reactions in complete kinematic experiment
- Simple model for studies of continuum in direct reaction
- Correlation measurements (Alignment and interference effects)
- Some illustrative examples



(d, p)-reaction kinematics

experimental approaches

(d, p)-reaction in the inverse kinematic

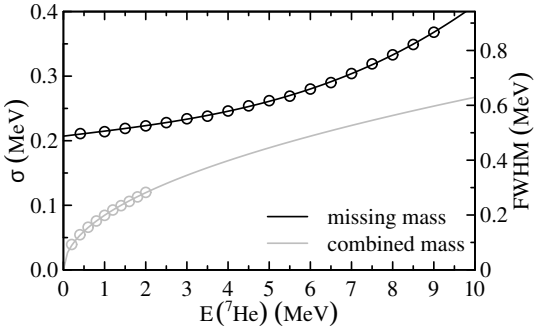


"Redundant" kinematic

- Background suppression
- Experimental resolution improving
- Correlations measurement

Combined mass method

- Registration of the recoil and light decay fragment
- Significant reducing of error in the decay energy reconstruction



Quasi-free scattering model in the frame of PWBA

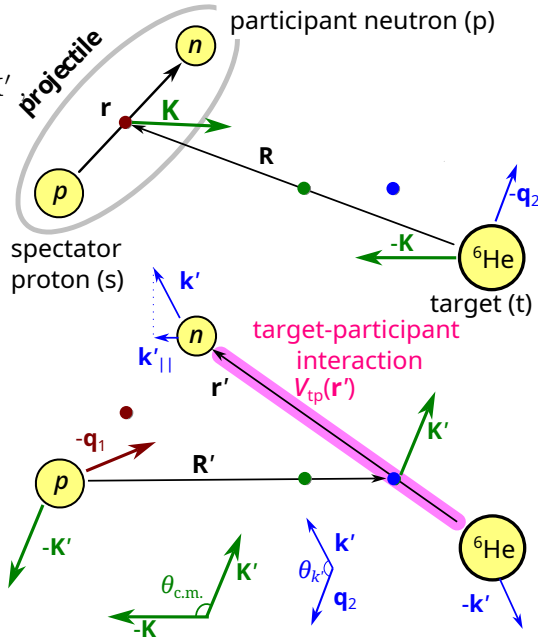
- Transferred momenta

$$\mathbf{q}_1 = \frac{M_s}{M_s + M_p}\mathbf{K} + \mathbf{K}' \ , \ \mathbf{q}_2 = \mathbf{K} + \frac{M_t}{M_t + M_p}\mathbf{K}'$$

- Amplitude

$$T_{\mu'_p,\mu'_s,\mu_b}(\mathbf{K}', \mathbf{k}', \mathbf{K}) = \sum_{\mu_p} T^{\dagger}_{\mu'_p,\mu_p}(\mathbf{k}', \mathbf{q}_2)\ \Phi_{\mu'_s,\mu_p,\mu_b}(\mathbf{q}_1) \ ,$$

- Three-fold differential cross section and five-fold differential cross section can be obtained in semi-analytical form
- $\cos\theta_{k'}$ — invariant kinematic variable



Alignment effects in correlation

"Forward" and "Backward"

$$\cos\theta_{k'} \geq 0 \text{Forward}$$

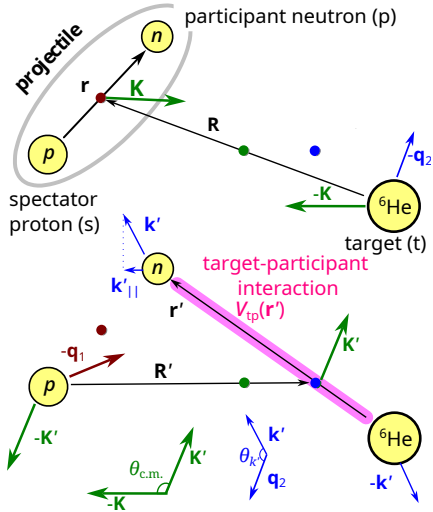
$$\cos\theta_{k'} < 0 \text{Backward}$$

$$\cos\theta_{k'} \equiv (\hat{k}', \hat{q}_2)\ , \quad \delta^{j_1 l_1}_{j_2 l_2} = \delta_{j_1 l_1} - \delta_{j_2 l_2}\ .$$

$$\frac{d\sigma}{d\cos\theta_{k'}} \sim \frac{1}{2}\, a^2_{s_{1/2}} + \frac{1}{2}\, a^2_{p_{1/2}} + \frac{1}{4}\, a^2_{p_{3/2}}\,(1 + 3\cos^2\theta_{k'})$$
$$+\ \sqrt{2}\, a_{p_{1/2}} a_{p_{3/2}}\,(3\cos^2\theta_{k'} - 1)\,\cos\big(\delta^{p_{3/2}}_{p_{1/2}}\big)$$
$$+ a_{s_{1/2}} \cos\theta_{k'}\left[a_{p_{1/2}}\cos\big(\delta^{p_{1/2}}_{s_{1/2}}\big) + \sqrt{2} a_{p_{3/2}}\cos\big(\delta^{p_{3/2}}_{s_{1/2}}\big)\right]\ .$$

Asymmetry

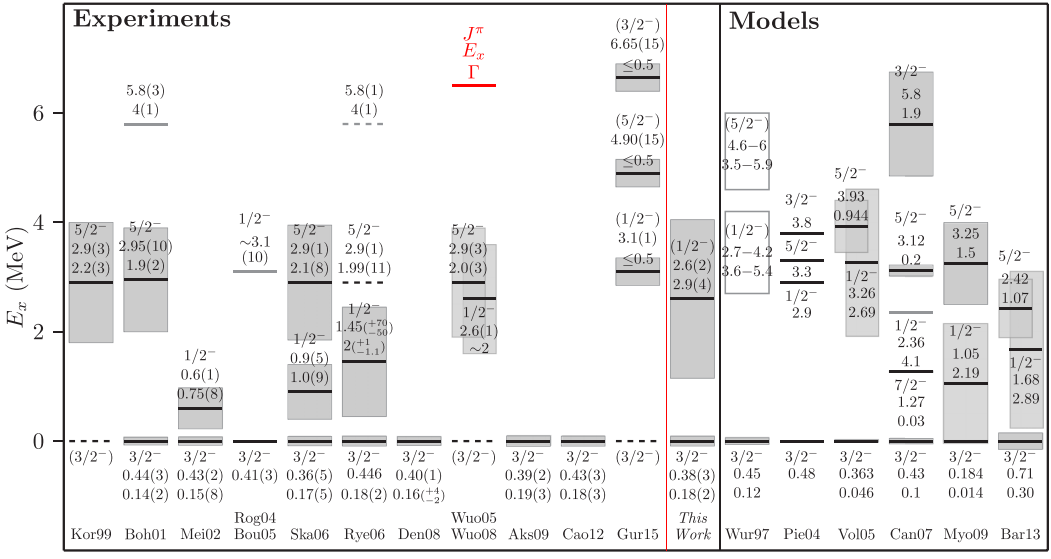
$$R^{(\mathrm{bf})} = \frac{a_{s_{1/2}} a_{p_{1/2}}\cos\big(\delta^{p_{1/2}}_{s_{1/2}}\big)}{a^2_{s_{1/2}} + a^2_{p_{1/2}} + a^2_{p_{3/2}}} +$$
$$\frac{a_{s_{1/2}}\sqrt{2} a_{p_{3/2}}\cos\big(\delta^{p_{3/2}}_{s_{1/2}}\big)}{a^2_{s_{1/2}} + a^2_{p_{1/2}} + a^2_{p_{3/2}}}\ .$$



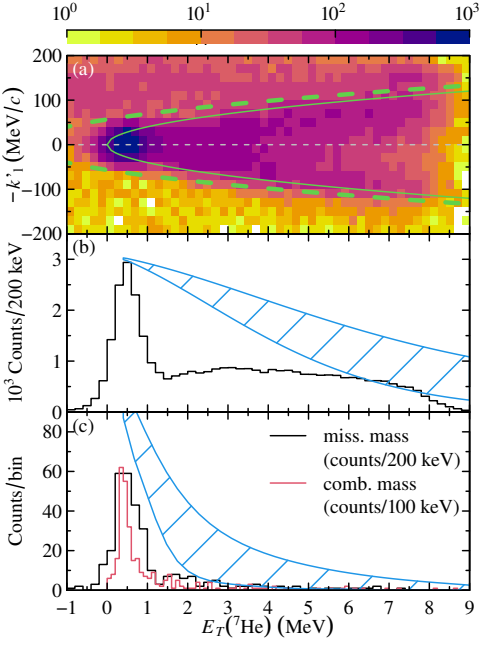
- asymmetry in $\cos\theta_{k'}$ distribution connected with interference
- $\cos\theta_{k'}$ distribution represented as a sum of the orthogonal polynomial

Some illustrative example

F. Renzi, et. al., Phys. Rev. C **94**, 024619 (2016)



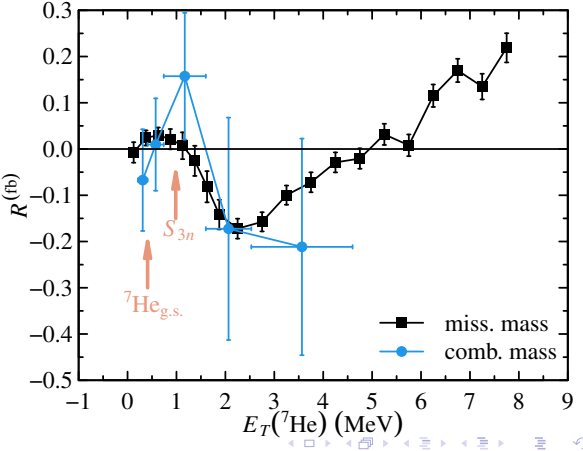
^{7}He example



A. A Bezbakh, et. al., Int. J. Mod. Phys. E **33**, 2450002 (2024)

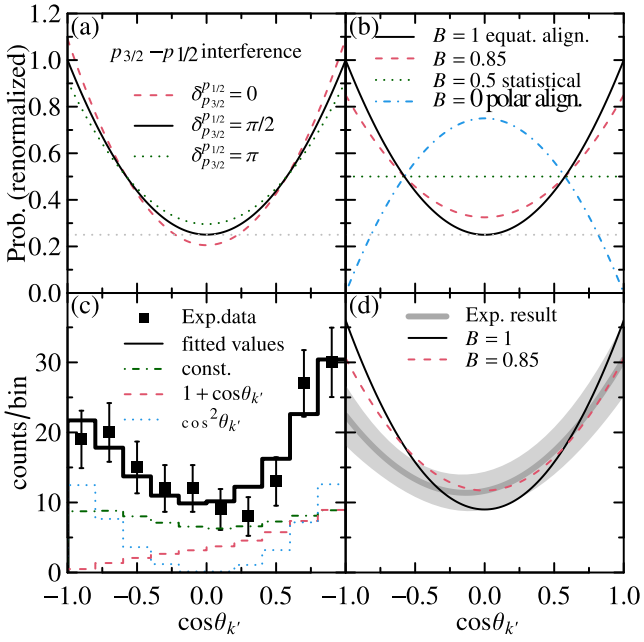
M. S. Golovkov, et. al., Phys. Rev. C **109**, L061602 (2024)

Asymmetry



Alignment and $\cos\theta_{k'}$ distribution

$$B = \frac{W_{M=\pm 1/2}}{W_{M=\pm 1/2} + W_{M=\pm 3/2}} \approx 1,$$



^{9}He example

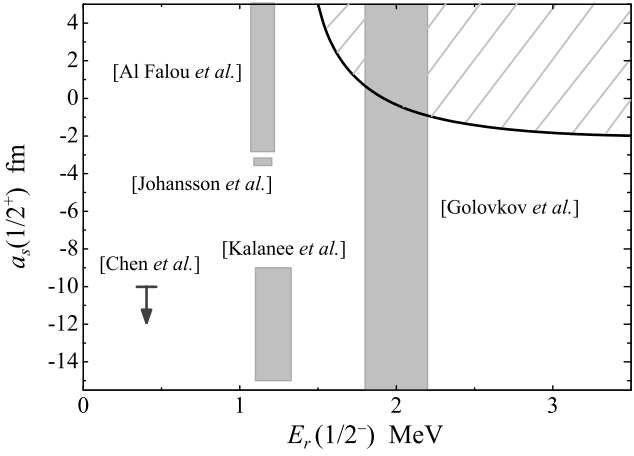
- There are a lot of works with contradicting conclusions about ^{9}He structure

The best experiment

M. S. Golovkov, et. al., Phys. Rev. C **76**, 021605(R) (2007)

However statistic was not enough for precise estimate of s-wave interaction parameters

- High statistic experiment resolve the ^{9}He problem



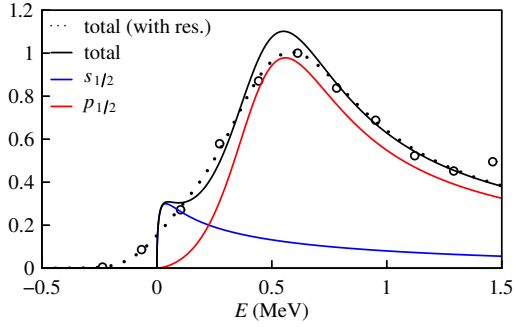
^{10}Li example

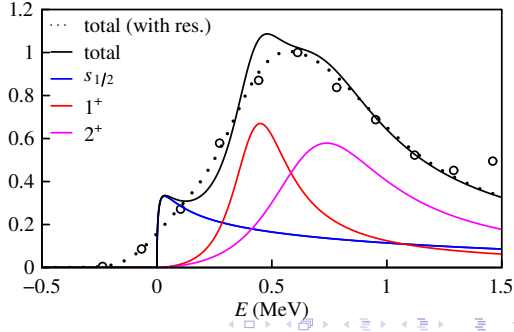
problems:

- s-wave interaction in $^{9}\mathrm{Li} + n$ interaction
- spin-spin split in ^{10}Li states

Prospective experiment:

- energy resolution improvement
- correlation studies with high statistic
- studies of the ^{10}Li in complimentary experiment in transfer and knockout reactions





Summary

- Studies of the exotic $1p$-shell nuclei require new experimental research on a new quality level.
- The approach discussed in the report can be applied to study a number of nuclear systems in the (d, p) reaction.
- Presented material is a result of a longtime experimental and theoretical studies

M. S. Golovkov, et. al., Phys. Rev. Lett., **93**, 262501-1-4 (2004)

M. S. Golovkov, et. al., Phys. Rev. C **72**, 064612 (2005)

M. S. Golovkov, et. al., Phys. Rev. C **76**, 021605(R) (2007)

S. I. Sidorchuk, et. al., Phys. Rev. Lett., **108** 202502 (2012)

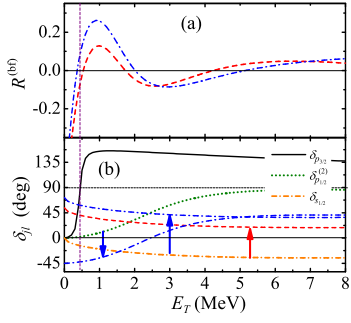
V. Chudoba, et. al., Phys. Lett. B **708** 6 (2012)

V. Chudoba, et. al., Phys. Rev. C **98**, 054612 (2018)

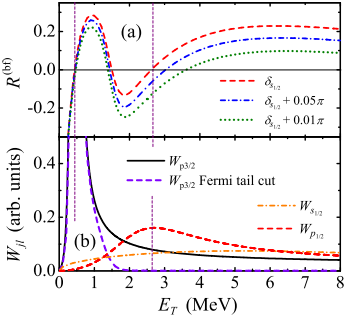
M. S. Khirk, et. al., arXiv 2503.17859 (submitted to Phys. Rev. C)

Backward-forward asymmetry in ^{7}He

Phase shift variation



Suppression of $p_{3/2}$



The $s_{1/2}$ resonant state