# $^{10}$Li as Borromean Nucleus Subsystem

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# Limits of the nuclear structure

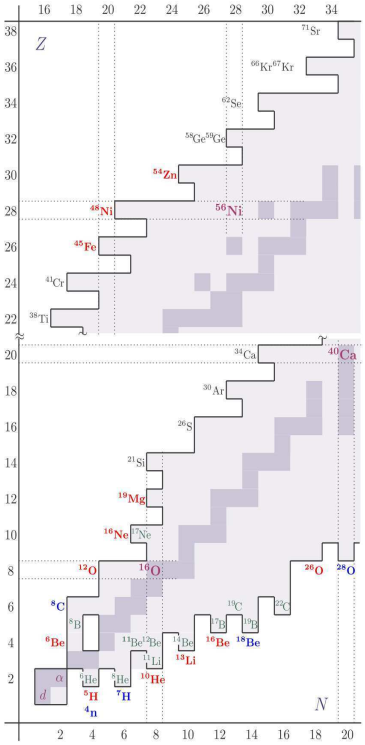
## Outline

- Nuclear structure near the drip-line
- Borromean nuclei phenomenon
- The problem of $^{10}\mathrm{Li}$
- Nuclear structure studies in direct reactions
- $^{11}\mathrm{Li}$ ground state calculations

The nuclear drip-lines have been reached for light and intermediate mass nuclei.

## “Exotic” nuclear structure

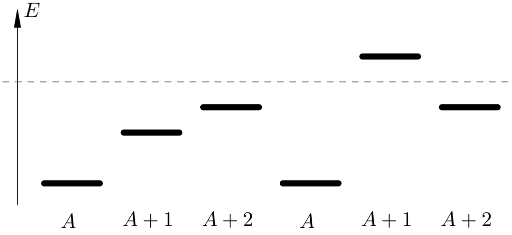
- Halo-nuclei
- Borromean nuclei
- direct $2p$- $2n$- $4n$- decays
- $p$- $2p$- ($2n$- $4n$- ) radioactivity



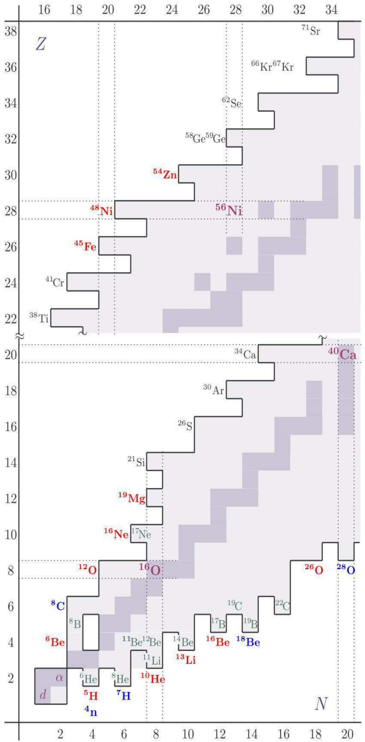
# Borromean nuclei

## related phenomena

- $2n$- $2p$-halo
- direct $2n$- $2p$-decay
- $2n$- $2p$-radioactivity




- borromean nuclei are not so exotic
- cluster model provide good description for borromean states.



# Borromean nucleus in three-body model

## 3-body Schrodinger Equation

$$[H_0 + V_{NN} + V_{CN_1} + V_{CN_2} + V_3]\,\Psi = 0$$

- $V_3$ — collective model potential for fine-tuning
- HH-method is used for SE solution

## hyper-spherical harmonic method

$$\rho^2 = \frac{A_1 A_2 A_3}{A_1 + A_2 + A_3}\left[\frac{r_{12}^2}{A_3} + \frac{r_{13}^2}{A_2} + \frac{r_{23}^2}{A_1}\right]$$

$$\Psi = \sum \psi_{K\gamma}(\rho)\mathcal{J}_{\mathcal{K}\gamma}(\otimes_{\bigtriangledown})$$

Solution of SE reduce to solution of ODE system.

# Experimental studies of $^{10}\mathrm{Li}$ I (How to?)

## Elastic scattering

- Radioactive ion ($^{9}\mathrm{Li}$) - $n$
- scattering phaseshifts can be directly obtained
- Such kind of experiments are technically impossible due to short lifetime of participants

## Elastic scattering for isotopic analog

- Radioactive ion ($^{9}\mathrm{Li}$) - $p$.
- This channel has same nuclear interaction.
- Problem of virtual states.

## Direct reactions

$$d(^{9}\mathrm{Li},p)^{10}\mathrm{Li}$$
$$p(^{11}\mathrm{Li},pn)^{10}\mathrm{Li}$$
$$p(^{11}\mathrm{Li},d)^{10}\mathrm{Li}$$
$$t(^{10}\mathrm{Be},{}^{3}\mathrm{He})^{10}\mathrm{Li}$$
$$\cdots$$

- Two ways:
  - Stripping of target
  - Knockout from projectile
- Data about $^{9}\mathrm{Li}-n$ interaction are encapsulated in process amplitude;
- One should analyze influence of reaction mechanism on $^{10}\mathrm{Li}$ continuum population.

# Experimental studies of $^{10}$Li II (Some history)

T. Fortune, EPJA **54** (2018) 51

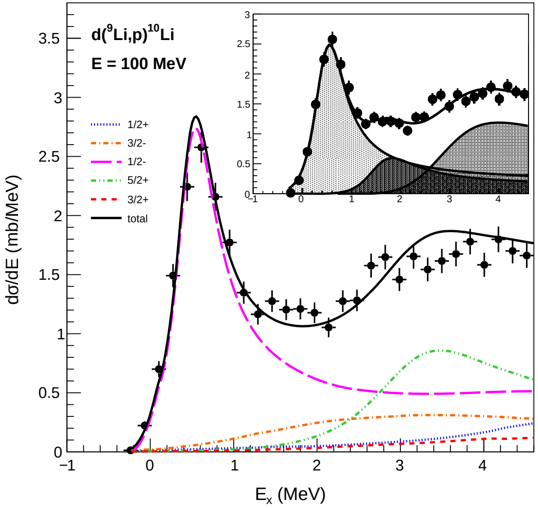
Table 13. Results of various experiments for low-lying states of $^{10}$Li (energies and widths in MeV).

| Year | Reaction | $E_r$ | | $\Gamma$ | | Ref. |
|---|---|---|---|---|---|---|
| 1997 | $^{10}$Be($^{12}$C,$^{12}$N) | 0.24(4) | | 0.10(7) | | [243] |
| 1999 | $^{9}$Be($^{9}$Be,$^{8}$B) | 0.50(6) | | 0.40(6) | | [244] |
| 1999 | fragmentation | $< 0.05$ | | | $s$ | [245] |
| 2001 | $p$ removal from $^{11}$Be | | | | g.s. is $s$ | [246] |
| 2003 | $^{9}$Li($d,p$) | 0.35(11) | | $< 0.32$ | | [242] |
| | | or $< 0.2$ | | – | | |
| | | plus 0.77(24) | | $< 0.62$ | | |
| 2006 | $^{9}$Li($d,p$) | $\sim 0$ | | | $s$ | [247] |
| | | $\sim 0.38$ | | $\sim 0.2$ | $p$ | |
| 2015 | 2$p$ removal from $^{12}$B | 0.11(4) | | 0.2 | | [248] |
| | | 0.50(10) | | 0.8 | both $p$ | |
| 2016 | $^{11}$Li($p,d$) | 0.62(4) | | 0.33(7) | $p$ | [249] |

- $^{10}$Li has been studied many times
- Interpretation of the results of different works contradict each other.

# Experimental studies of $^{10}$Li III (Summary)

Cavallaro et. al., PRL **118** (2017) 012701




Experiments with RIB provide qualitative improvement of experimental data

## $^{10}$Li structure

- single-particle $p$-wave resonance with

$$E_r \sim 0.6 \text{ MeV}$$

? virtual state vs. $s$-wave resonance

? value of spin-spin splitting

# Studies of continuum in direct reactions

For better understanding of continuum populated in direct one should estimate effects connected with Initial State Structure and Reaction mechanism.

## Model with source

$$T_{IF} = \langle \Psi_I | V | \Psi_F \rangle ;$$
$$\Psi_F = \Psi_{^{10}\mathrm{Li}} \Psi' ;$$
$$T_{IF} \sim \left\langle \Phi \middle| \Psi_{^{10}\mathrm{Li}} \right\rangle$$

- $\Psi_{^{10}\mathrm{Li}}$ — Wave Function responsible for (FSI)
- $\Phi$ — source function (responsible for ISS)
- It is possible to study the scale of ISS effects using the model with source.

## Model Source

$$\Phi = C_0 r^{l+1} \exp\left[C_1 r / r_0\right]$$

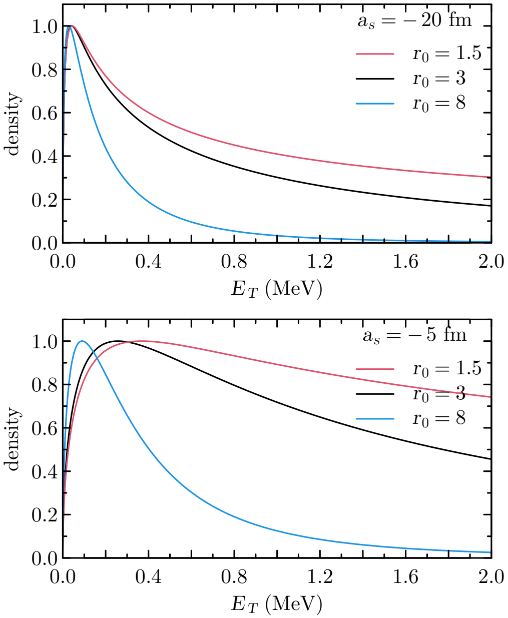
- $r_0$ – effective size of source;
- "compact" source correspond to transfer reactions
- "large" source correspond to knockout from drip-line nuclei

## $\Psi_{^{10}\mathrm{Li}}$

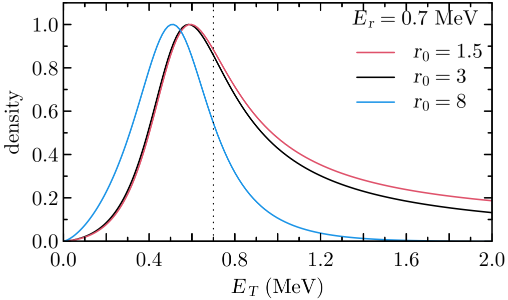
- one-channel SE solution
- Woods-Saxon potential

# ISS and FSI effects on example of $^{10}\mathrm{Li}$

## $s$-wave

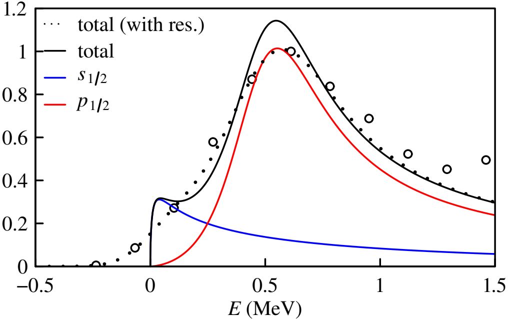



## $p$-wave

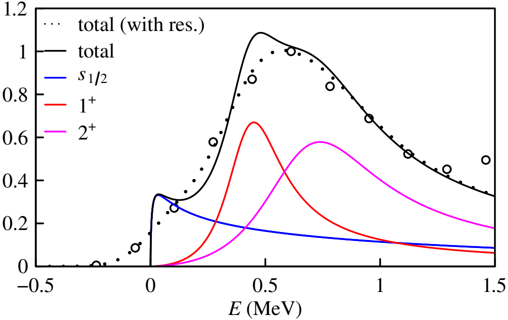



- $s$-wave (and $p$-wave far away from peak) behavior drastically change with the source size variation
- It is important to accurately treat ISS-effects for spectrum decomposition.

# Possible $^{10}\mathrm{Li}$ spectrum decomposition




| $E_r(\delta)$ | $\Gamma$ |
|---|---|
| 0.7 | 0.58 |




| | $E_r$ | $\Gamma$ |
|---|---|---|
| $1^+$ | 0.5 | 0.32 |
| $2^+$ | 0.9 | 0.68 |

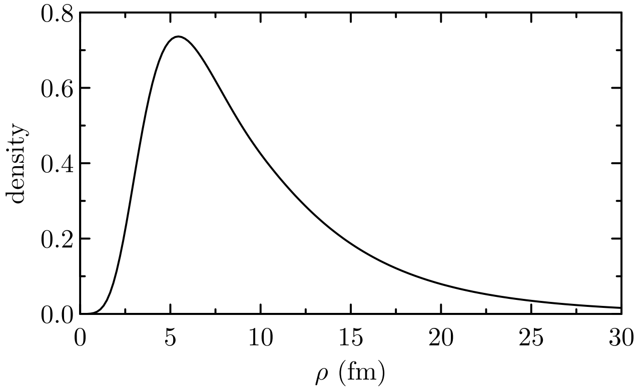
- One can not make unique decomposition of $^{10}\mathrm{Li}$ spectrum using only exclusive spectrum (decay energy distribution).
- One needs to treat reaction mechanism effects in conjunction with detector efficiency.

# $^{11}$Li ground state calculations

## Approximation

- $s$- and $p$-wave potentials reproduce $^{10}$Li
- $ss$-split is neglected
- core spin is neglected

- We reproduce g.s. energy
- Collective potential $V_3 \sim 0.06$ MeV
- $r_{\text{mat.}} \sim 3.1 - 3.2$ fm ($r_{\text{mat.}}(\text{Exp}) = 3.31$ fm )



# Summary

- The problem of $^{10}\mathrm{Li}$ nuclear system is a partial case of quite general problem.
- Reaction mechanism can significantly modify spectral density behavior.

- Using simple approximation we qualitatively reproduce $^{10}\mathrm{Li}$ spectrum and $^{11}\mathrm{Li}$ ground state.