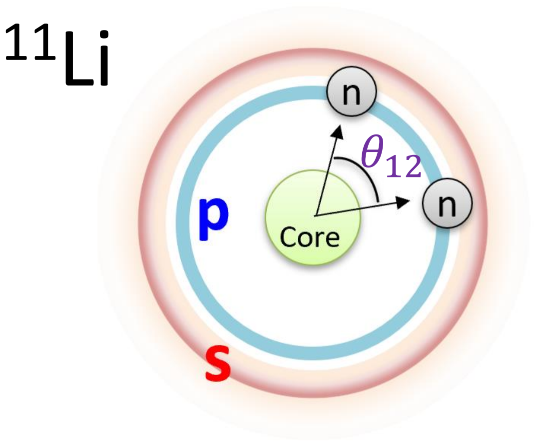
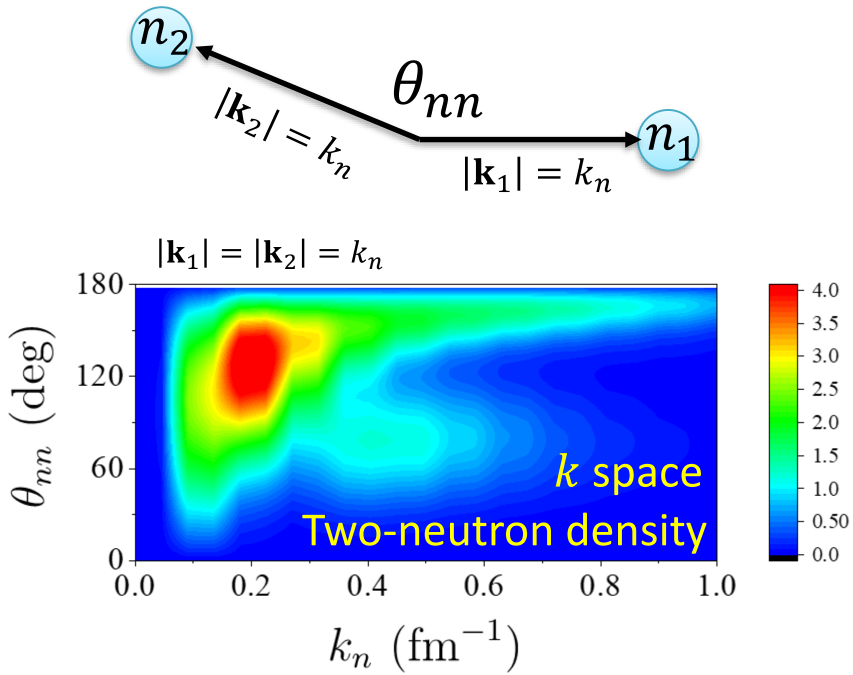
Momentum-space structure of dineutron in ^{11}Li and ^{22}C

Masayuki Yamagami (University of Aizu)





Structure of dineutron and *the probe*

Dineutron

- Compact $S=0$ pair of two neutrons
- Enhanced in low-density medium as neutron halo

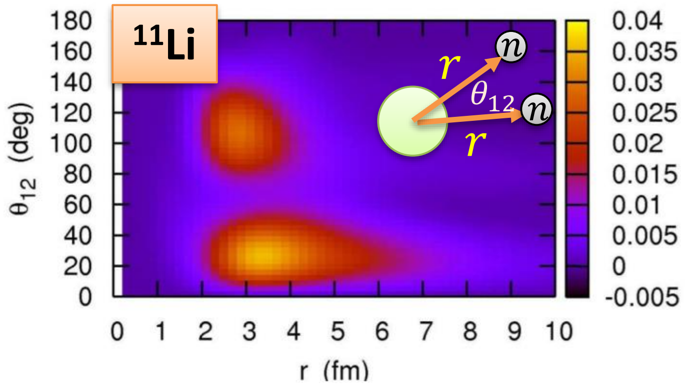
[*For recent review,* H. Sagawa and K. Hagino, Eur. Phys. J. A51, 102 (2015)]

Question of long standing

- How can we probe the 2n density $\rho_2(\mathbf{r}_1, \mathbf{r}_2)$?
- Not only $|\boldsymbol{r}_1| = |\boldsymbol{r}_2|$, but also $|\boldsymbol{r}_1| \neq |\boldsymbol{r}_2|$

Two-neutron density (cal)

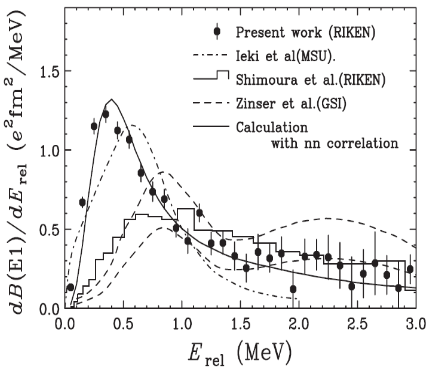
K.Hagino, H.Sagawa, PRC 72, 044321 (2005)



Numerous studies for Borromean nuclei such as ^{11}Li

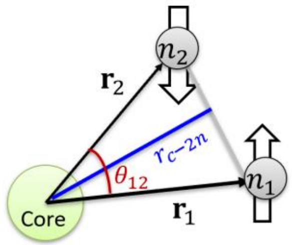
E1 strength in ^{11}Li (exp)

T. Nakamura *et al.*, PRL96, 252502 (2006)



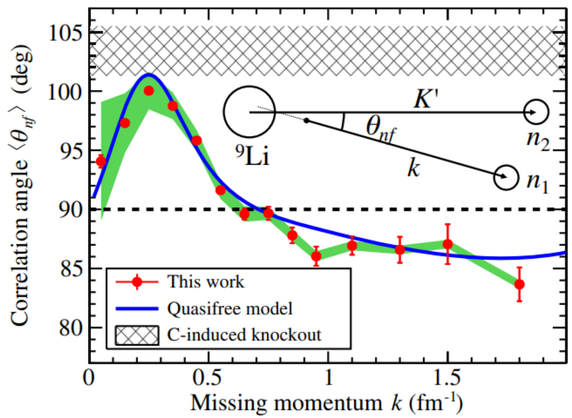
$$\sqrt{\langle r^2_{c-2n} \rangle} = 5.01(32)\ \text{fm}$$

$$\langle \theta_{12} \rangle = 48^{+14}_{-18}\ \text{degree}$$



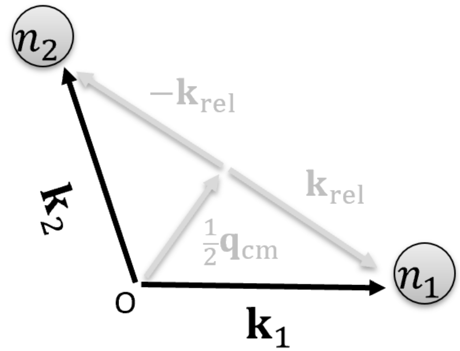
Mean correlation angle $\langle \theta_{nf} \rangle$ in ^{11}Li (exp)

Y.Kubota et al.,PRL125, 252501 (2020)



In this talk,
I discuss how $\langle \theta_{nf} \rangle$ relates to $\rho_2(\mathbf{k}_1, \mathbf{k}_2)$ in ^{11}Li and ^{22}C.

Three-body model in momentum space



Three-body Hamiltonian (momentum space)

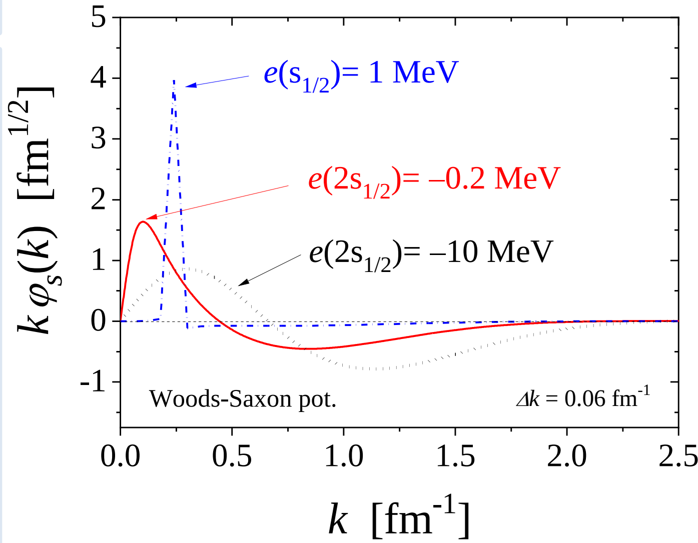
$$H = h_{\text{core}-n}(1) + h_{\text{core}-n}(2) + \underbrace{V_{nn}}_{\text{Valence } n\text{-}n} + \underbrace{\frac{\hbar^2}{A_c m}\mathbf{k}_1 \cdot \mathbf{k}_2}_{\text{Recoil term}}$$

- Diagonalized by using single-particle WF $\varphi_{lj}(k)$

Single-particle Schrödinger eq. (Integral eq.)

$$h_{\text{core}-n}\,\varphi_{lj}(k) = \frac{\hbar^2 k^2}{2\mu}\varphi_{lj}(k) + V_{\text{core}-n}[\varphi_{lj}] = \varepsilon_{lj}\,\varphi_{lj}(k)$$

- k-space rep. → Suitable for weakly-bound nuclei
- Woods-Saxon potential for $V_{\text{core}-n}$



$V_{\text{core}-n}$	**One-particle resonance**	**s-wave scattering length**
^{11}Li [1]	$E_R^{(exp)}(\boldsymbol{p}_{1/2}) = 0.54$ MeV [2]	$a_0 = -5.6$ fm
^{22}C (set C1)	$E_R(\boldsymbol{d}_{3/2}) = 0.9$ MeV [3,4]	$a_0 = -2.8$ fm [6]
^{22}C (set C2)	$E_R(\boldsymbol{d}_{5/2}) = 1.5$ MeV [5]	

[1] H.Esbensen et al.,PRC56, 3054 (1997)
[2] B. M. Young et al., PRC49, 279 (1994)
[3] E.C.Pinilla and P. Descouvemon, PRC 94, 024620 (2016),
[4] J.Singh et al.,Few-Body Syst. 60:50 (2019)
[5] N.A.Orr, EPJ Web of Conf.113, 06011 (2016)
[6] S.Mosby et al.,NPA 909, 69 (2013)

V_{nn}: Separable-type, finite-range n-n interaction

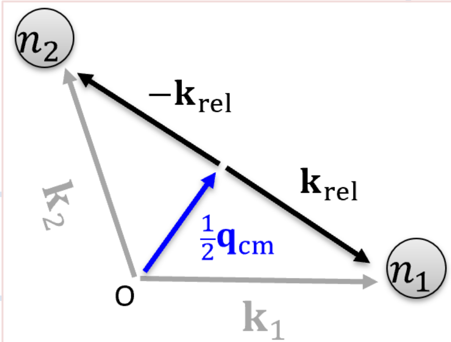
Yamaguchi-type potential [1]

$$V_{nn} = -\gamma(k_{\mathrm{rel}}) \cdot \gamma(k'_{\mathrm{rel}}) \quad \text{with} \quad \gamma(k_{\mathrm{rel}}) = \frac{u}{k_{\mathrm{rel}}^2 + \Lambda^2}$$

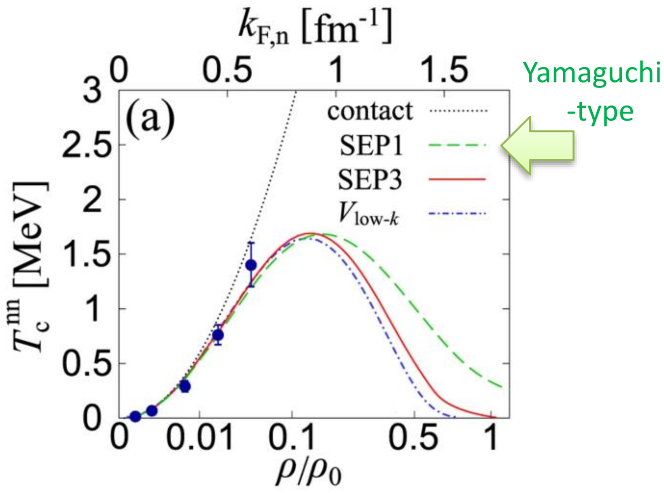
- Two-, Three-nucleon systems
- Pairing in nuclear matter [2]

Parameters u, Λ

$\Leftarrow$ Low-E ${}^1S_0$ n-n scattering



${}^1S_0$ neutron superfluid phase transition temperature T_{nn} [2]



⇩ Extension in this study

For Borromean nuclei

$$V_{nn} = -\gamma(k_{\mathrm{rel}})\eta(q_{\mathrm{cm}}) \cdot \gamma(k'_{\mathrm{rel}})\eta(q'_{\mathrm{cm}})$$

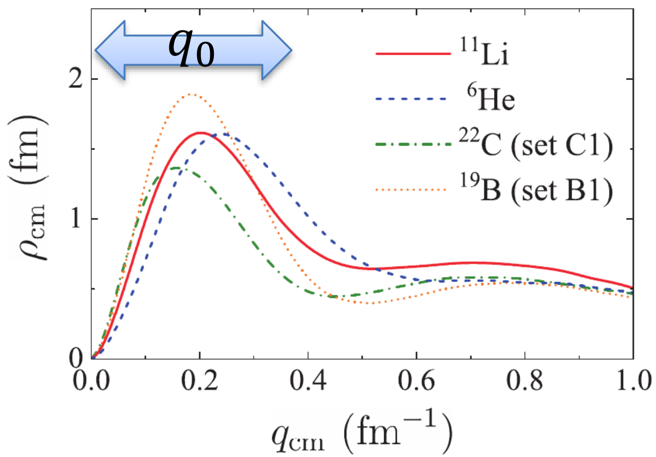
$$\eta(q_{\mathrm{cm}}) = \left(\sqrt{\pi} q_0\right)^{-3} e^{-(q_{\mathrm{cm}}/q_0)^2}$$

Parameter $q_0 = 0.359\ \mathrm{fm}^{-1}$ $\Leftarrow$ S_{2n} in ^{11}Li

Surface-type force

Note: Easy to use in density functional theory

Valence 2n density distribution



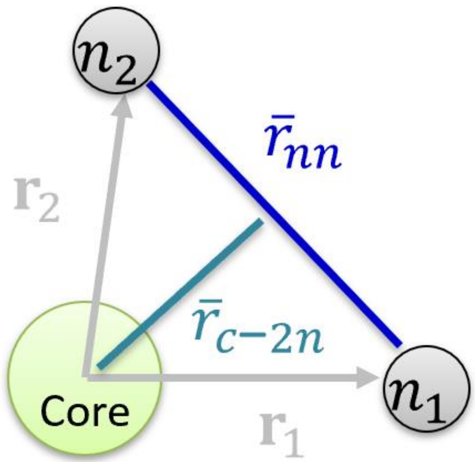
[1] Y. Yamaguchi, Phys. Rev. 95 (1954) 1628 [2] H. Tajima et al., Scientific reports 9, 18477 (2019)

Ground-state properties

		One-particle resonance (MeV)	2n separation energy S_{2n} (MeV)	Occupation prob. $(s_{1/2})^2$ (%)	Matter radius R_m (fm)	Core-2n distance $\bar{r}_{c-2n}$ (fm)	n-n distance $\bar{r}_{nn}$ (fm)
^{11}Li	**Cal.**	$\boldsymbol{p_{1/2}}$: 0.54 [1]	**0.369** [2]	**27.1**	**3.20**	**5.00**	**6.78**
	Exp.			35±4 [3]	3.12(16) [4]	5.01(32) [5]	6.6±1.4 [6]
^{22}C	**Cal.(set C1)**	$\boldsymbol{d_{3/2}}$: 0.9	**0.111**	**28.1**	**3.39**	**5.08**	**7.53**
	Cal.(set C2)	$\boldsymbol{d_{5/2}}$: 1.5	**0.202**	**32.9**	**3.41**	**5.20**	**7.55**
	Exp.		<0.32 [7]	-	3.44±0.08 [8]	-	-

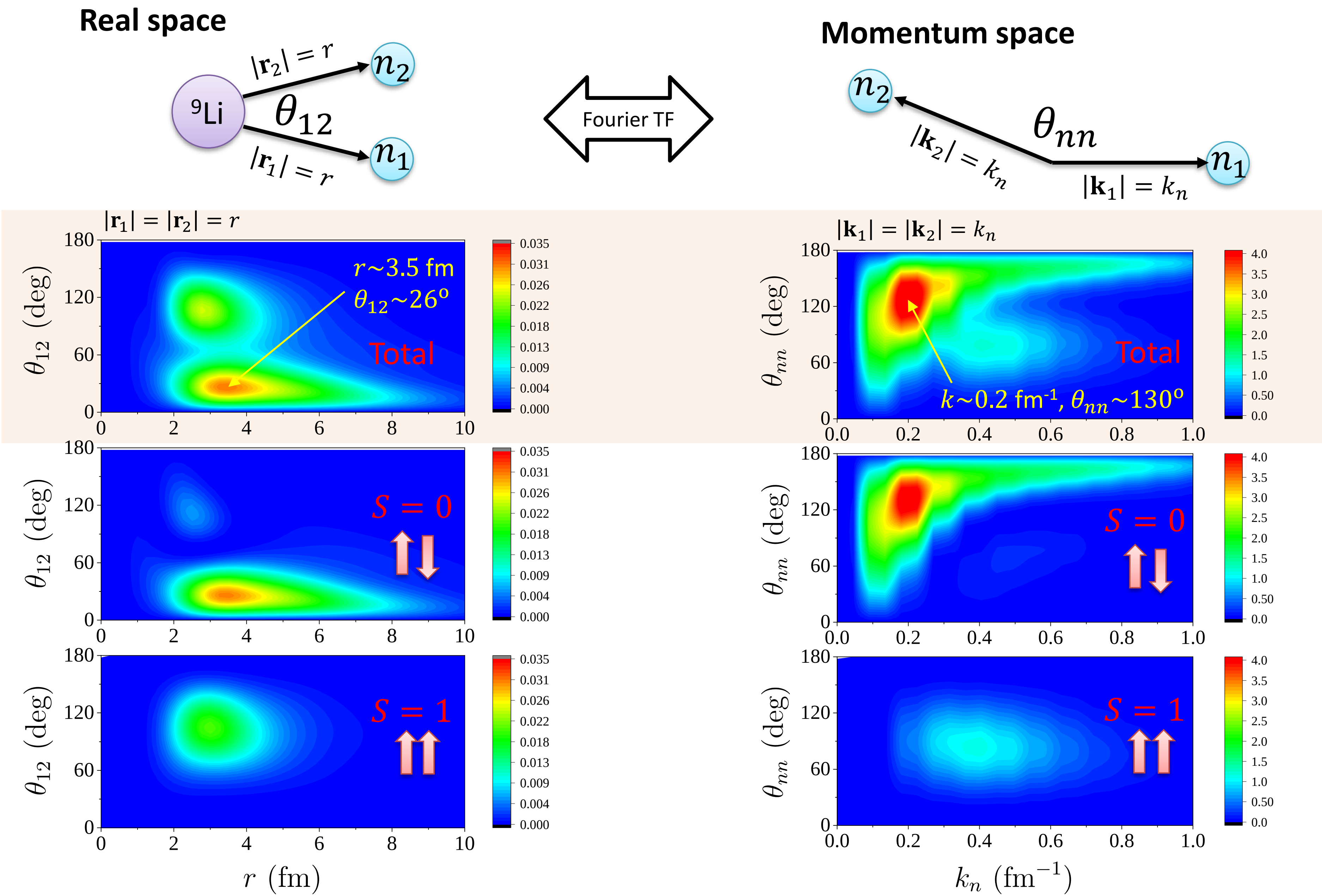
Input for V_{core-n}

Input for V_{nn}



[1] B. M. Young et al., Phys Rev. C49, 279 (1994)
[2] M. Smith et al., Phys. Rev. Lett. 101, 202501 (2008)
[3] Y. Kubota et al., Phys. Rev. Lett. 125, 252501 (2020)
[4] A. Ozawa et al., Nucl. Phys. A693, 32 (2001)
[5] T. Nakamura et al., Phys. Rev. Lett. 96, 252502 (2006)
[6] F. M. Marqués et al., Phy. Lett. B476, 219 (2000)
[7] L. Gaudefroy et al., Phys. Rev. Lett. 109, 202503 (2012)
[8] Y. Togano et al.,Phy. Lett. B 761, 412 (2016)

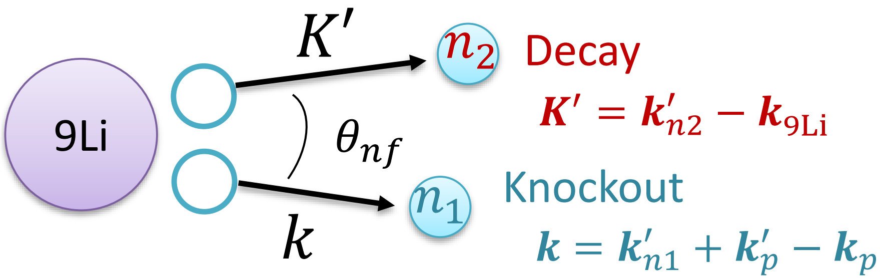
Two-neutron density in ^{11}Li

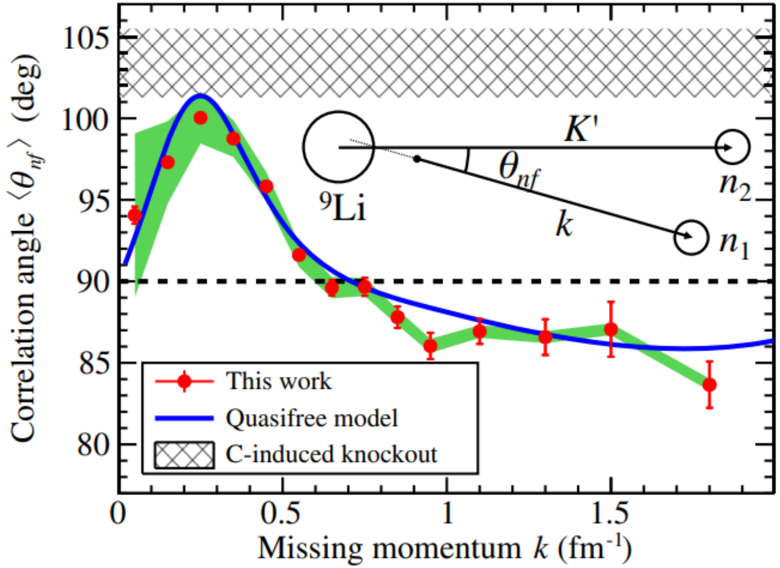


Mean correlation/opening angle

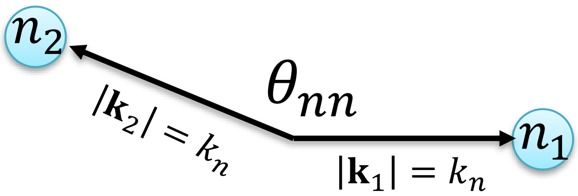
Exp: $^{11}\mathrm{Li}(p,p\,n_1)^{10}\mathrm{Li}^{*} \rightarrow {}^{9}\mathrm{Li} + n_2$

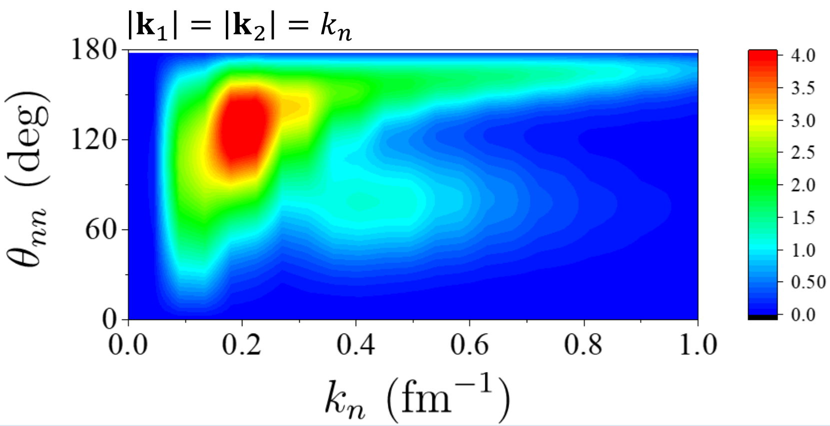
Y.Kubota et al.,PRL125, 252501 (2020)

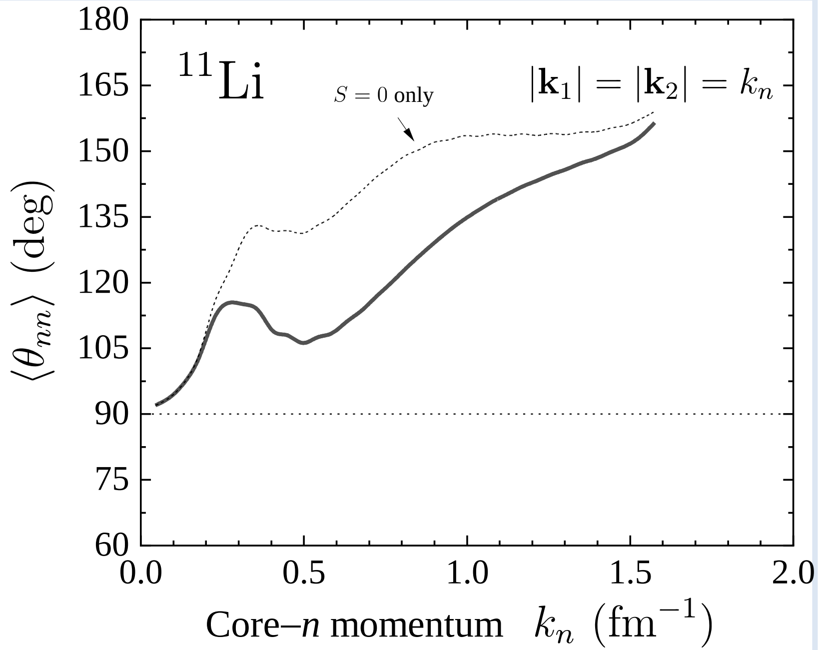




Momentum space (g.s.)



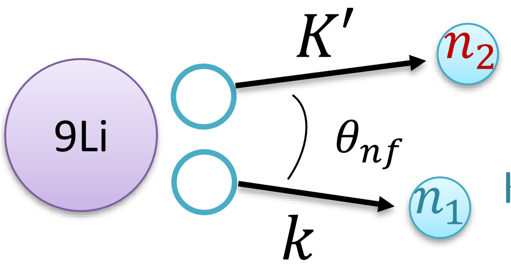




Different role between n_1 and n_2

Exp: $^{11}\mathrm{Li}(p,p\,n_1)^{10}\mathrm{Li}^* \rightarrow {}^{9}\mathrm{Li} + n_2$

Y.Kubota et al.,PRL125, 252501 (2020)

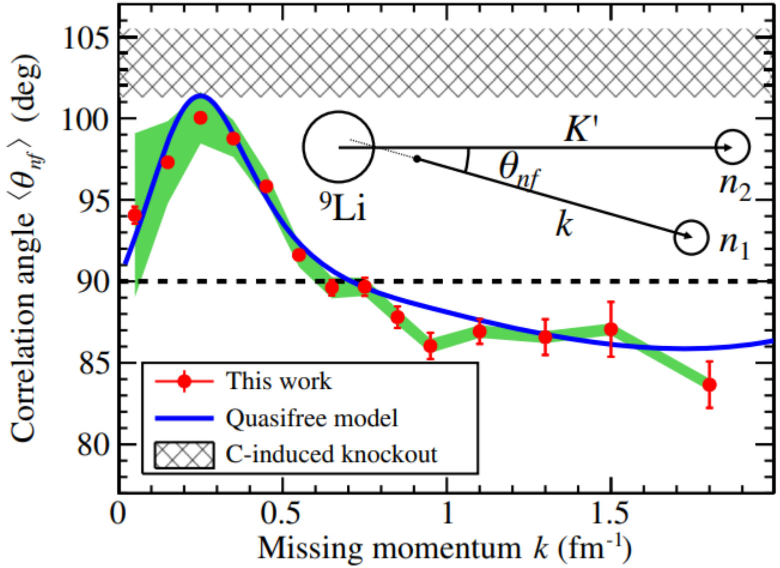


Decay

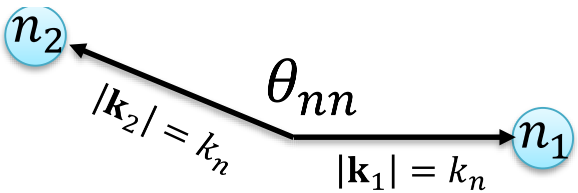
$\boldsymbol{K}' = \boldsymbol{k}'_{n2} - \boldsymbol{k}_{9\mathrm{Li}}$

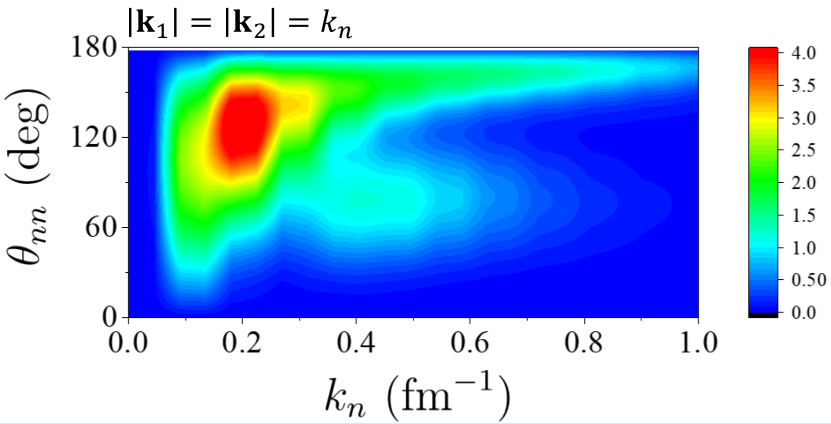
Knockout

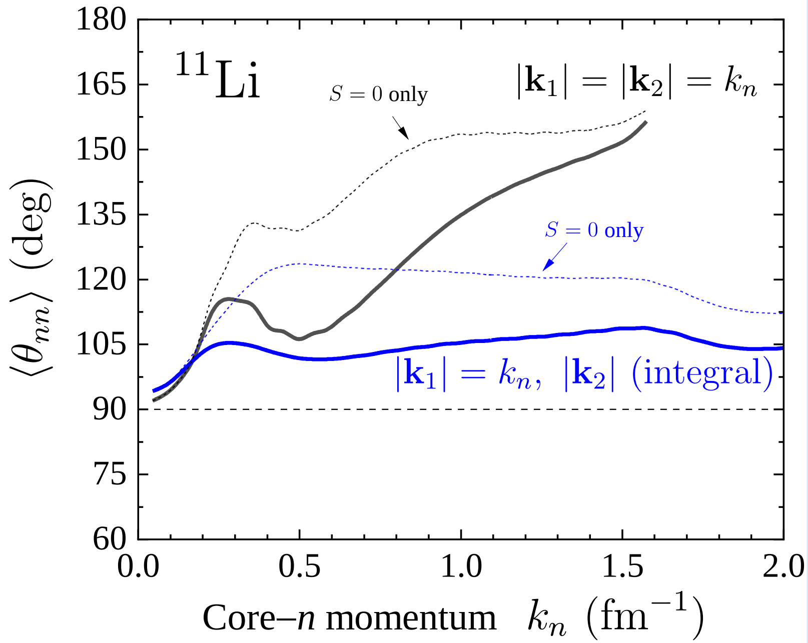
$\boldsymbol{k} = \boldsymbol{k}'_{n1} + \boldsymbol{k}'_{p} - \boldsymbol{k}_{p}$



Momentum space (g.s.)



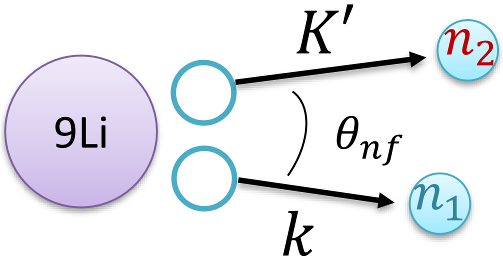




Surface effect on n_2

Exp: $^{11}\mathrm{Li}(p, p\, n_1)^{10}\mathrm{Li}^{*} \rightarrow {}^{9}\mathrm{Li} + n_2$

Y.Kubota et al.,PRL125, 252501 (2020)

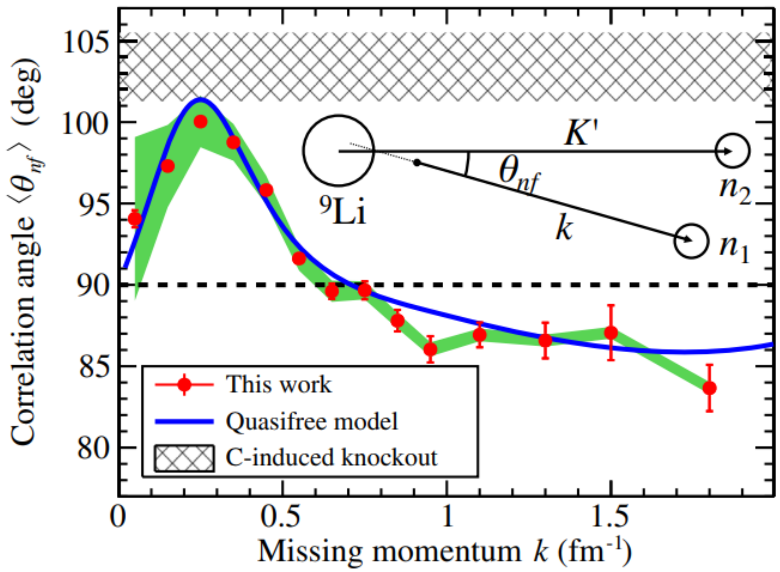


Decay @ "surface" only

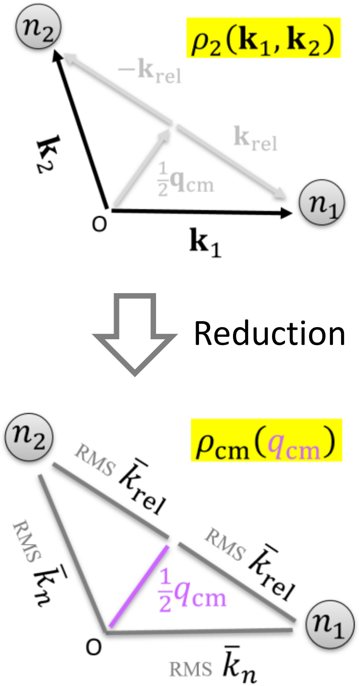
$\boldsymbol{K'} = \boldsymbol{k}'_{n2} - \boldsymbol{k}_{9\mathrm{Li}}$

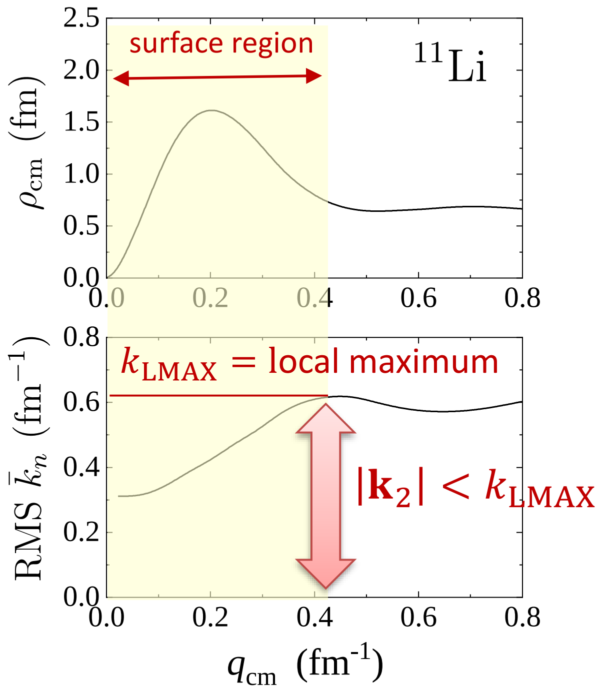
Knockout

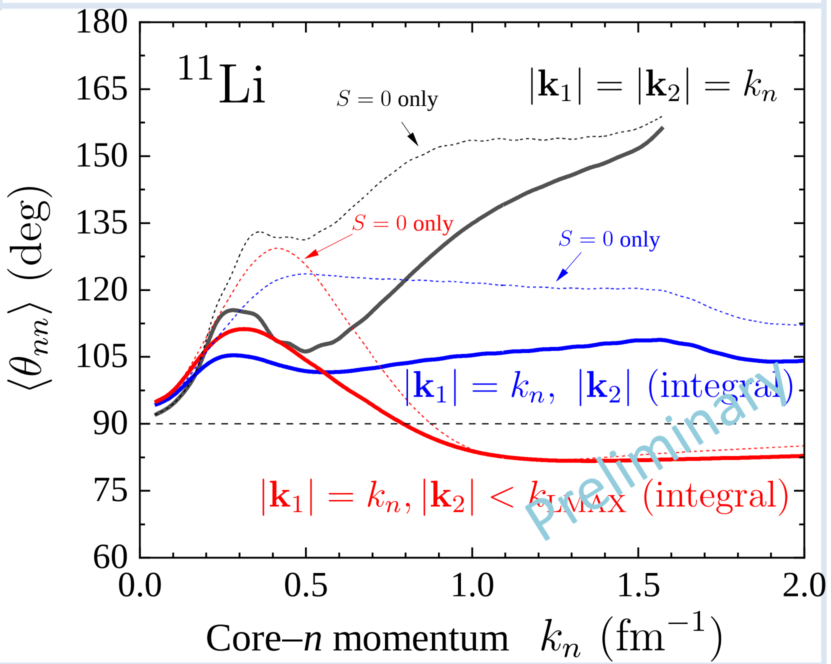
$\boldsymbol{k} = \boldsymbol{k}'_{n1} + \boldsymbol{k}'_{p} - \boldsymbol{k}_{p}$



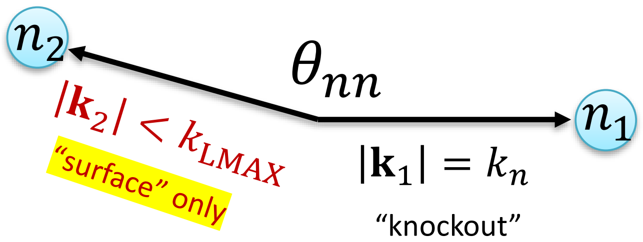
Definition of "surface" (in momentum space)

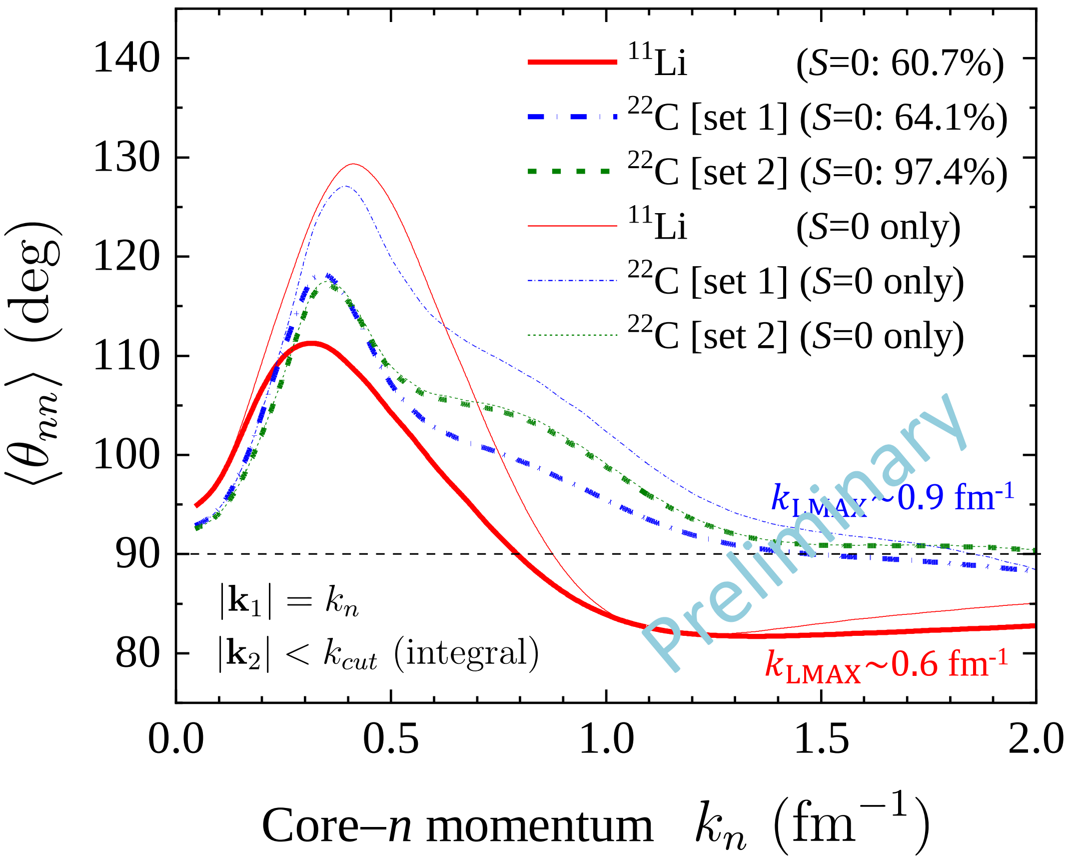


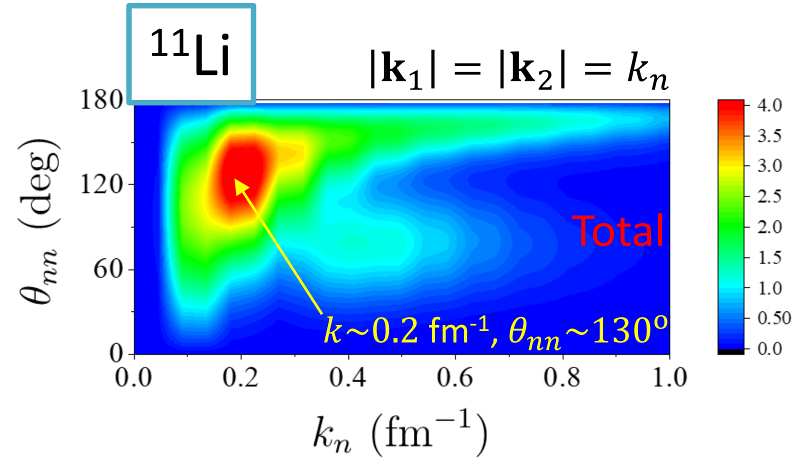


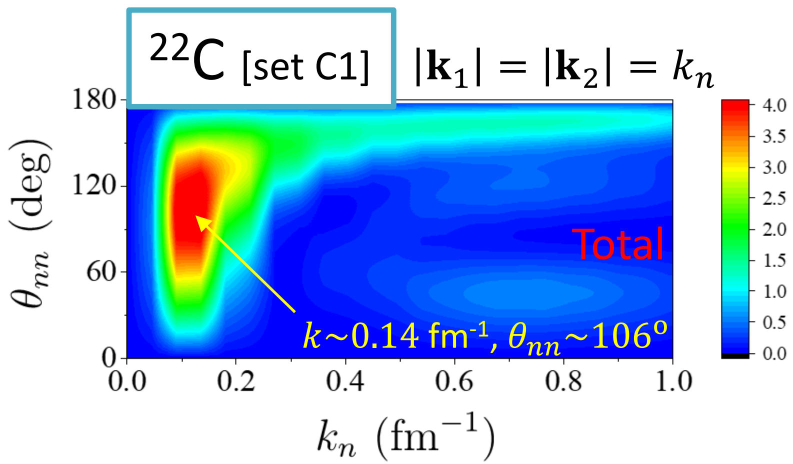


Mean opening angle in ^{11}Li and ^{22}C







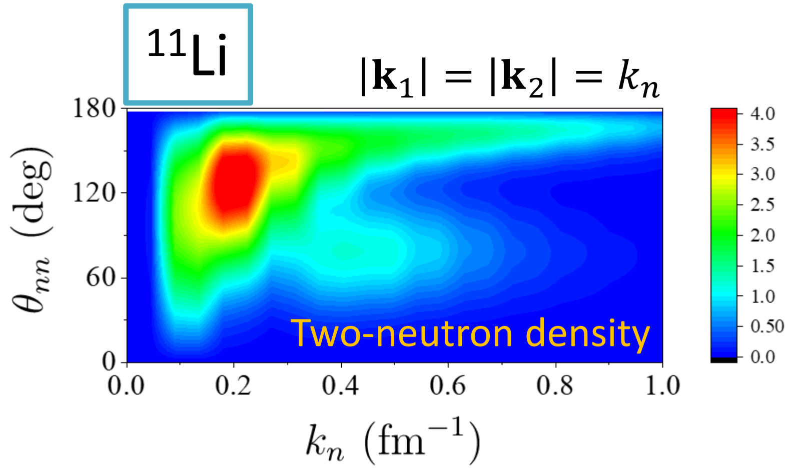


Summary

Topics: Momentum-space structure of dineutron in ^{11}Li and ^{22}C

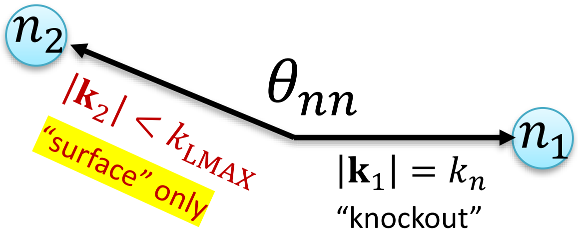
1. Development of calculation

- Three-body model in momentum space
- Separable-type, finite-range *n*-*n* interaction

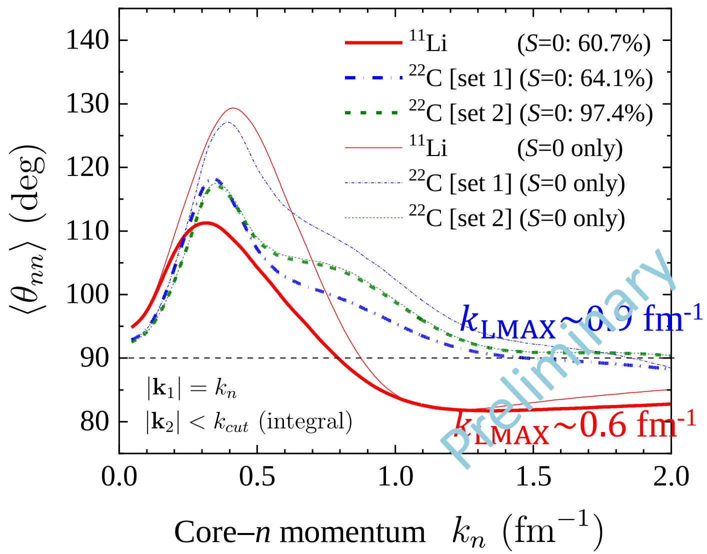


2. Discussion about dineutron

$\rho_2(\mathbf{k}_1, \mathbf{k}_2)$



- Mean opening angle $\langle\theta_{nn}\rangle$ as a function of $|\mathbf{k}_1| = k_n$
- Cutoff $|\mathbf{k}_2| < k_{\mathrm{LMAX}}$ for similarity to experimental $\langle\theta_{nf}\rangle$
  - ➢ k_{LMAX} = local maximum of $|\mathbf{k}_2|$ (Relative mom. k_{rel})
  - ➢ Relevant not only $|\mathbf{k}_1| = |\mathbf{k}_2|$, but also $|\mathbf{k}_1| \neq |\mathbf{k}_2|$



- $\langle\theta_{nf}\rangle \sim \langle\theta_{nn}\rangle$ can be a good probe of $\rho_2(\mathbf{k}_1, \mathbf{k}_2)$
  - ➢ Can distinguish between dineutron in ^{11}Li and ^{22}C