Experimental study of knockout reaction mechanism using ^{14}O at 60 MeV/nucleon

DREB2016
Direct Reactions with Exotic Beams

Outline:

1. Isospin dependence of nucleon correlation

2. Knockout reaction mechanism

3. Experimental Setup

4. Results and discussion

5. Summary

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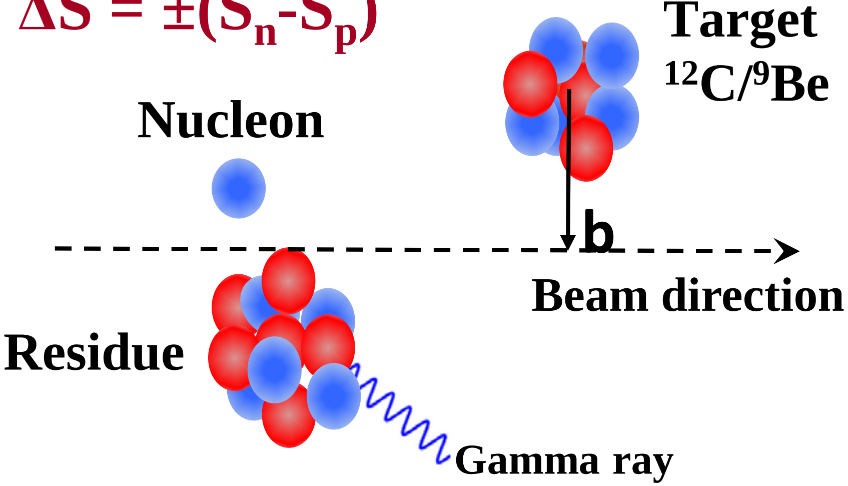
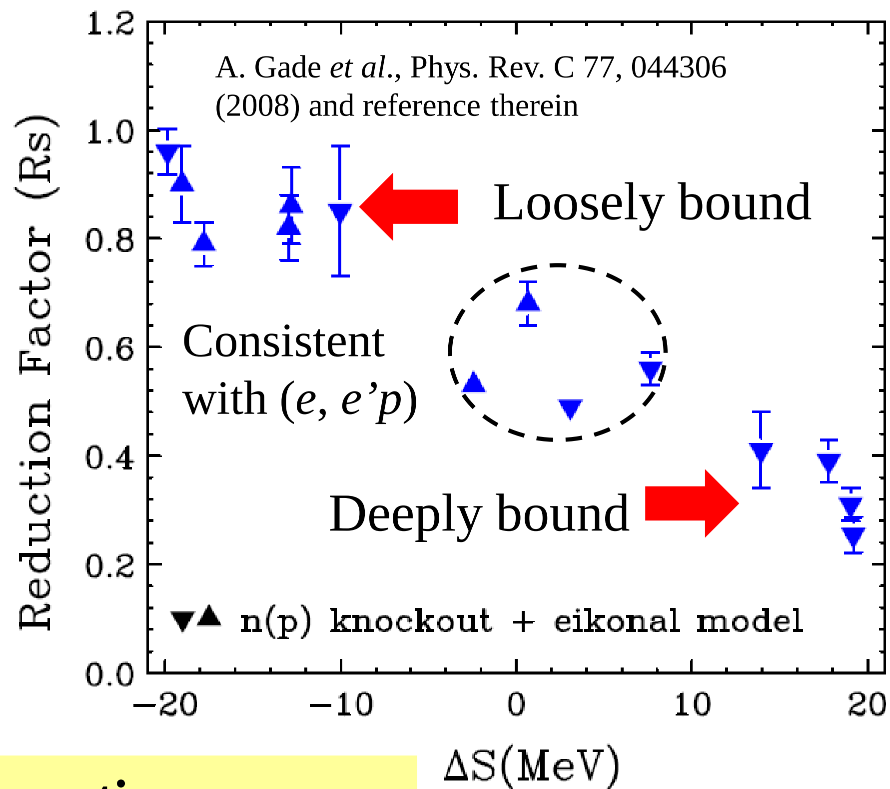
Isospin dependence of nucleon correlation

$R_s = \sigma_{exp} / \sigma_{th}$ → Structure model + reaction model

A. Knockout reaction

$\Delta S = \pm(S_n - S_p)$



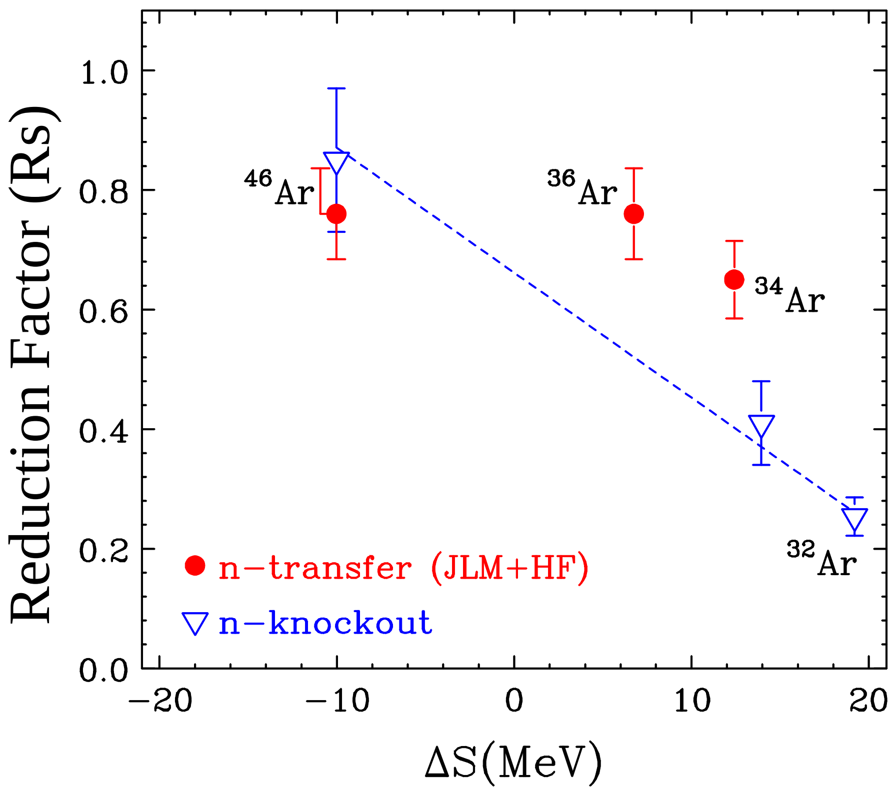


✓ R_s **strongly depends on separation energy**

→ More correlations are missing for deeply-bound nucleon in structure calculation, in case of the reaction model is correct

Isospin dependence of nucleon correlation

B. Transfer reaction



Q: Isospin Dependence ?

Knockout reactions: Yes & Strong

A. Gade *et al*., Phys. Rev. Lett. 93, 042501 (2004).)

Transfer reactions: Weak

^{34,36,46}Ar(*p, d*) at 33 MeV/u

J. Lee *et al*., Phys. Rev. Lett 104, 112701 (2010)

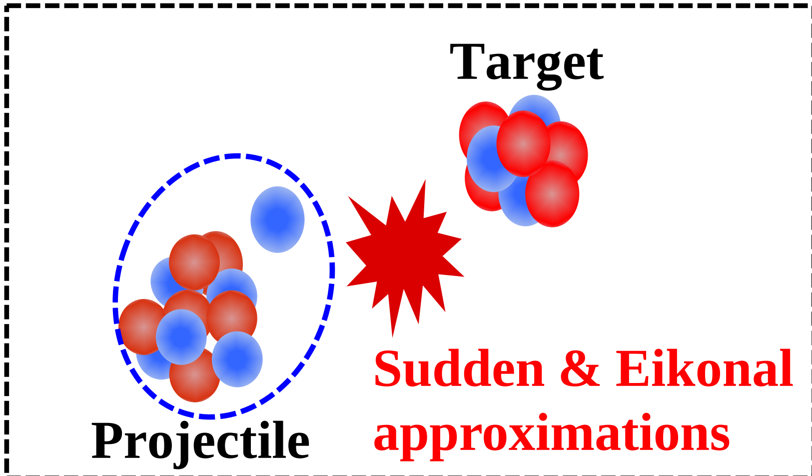
^{14}O(*d, t*)^{13}O , ^{14}O(*d,* ^{3}He)^{13}N at 18 MeV/u

F. Flavigny, *et al*., PRL 110, 122503 (2013)

Systematic difference between two probes !

→Need better understanding of deeply-bound nucleon removal mechanism !

Knockout Reaction--Eikonal Formalism



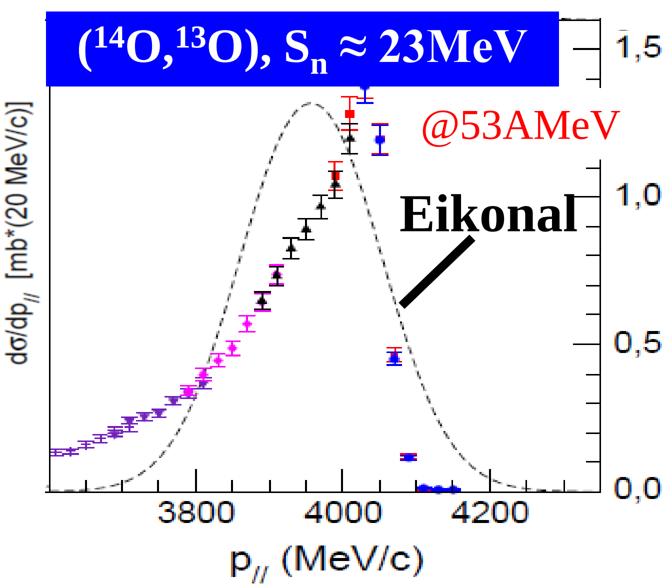
$$\sigma_{sp} = \sigma_{str} + \sigma_{dif} + \sigma_{C}$$

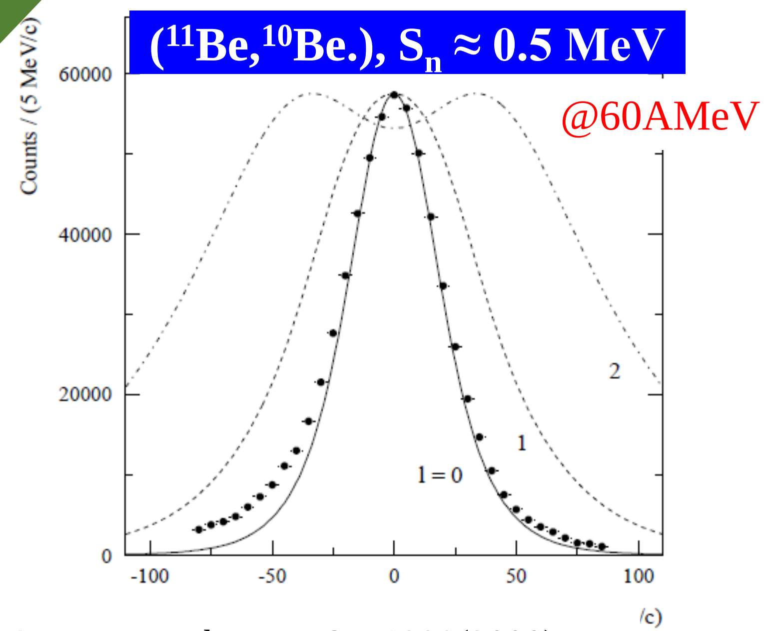
$$\sigma_{diff} = \sum_k \left| \langle \phi_k | \hat{S}_v \hat{S}_c | \phi_0 \rangle \right|^2$$

$$\sigma_{str} = \frac{\pi}{k^2} \sum \langle \phi_0 | \left(1 - |\hat{S}_v|^2 \right) |\hat{S}_c|^2 | \phi_0 \rangle$$

J. A. Tostevin *et al*., NPA682 320c(2001).
C.A.Bertulani, A.Gade CPC175 (2006) 372–380

→Successful for weakly bound nucleon.
→Questionable for deeply bound nucleon.
1) Beam energy 2) Separation energy…



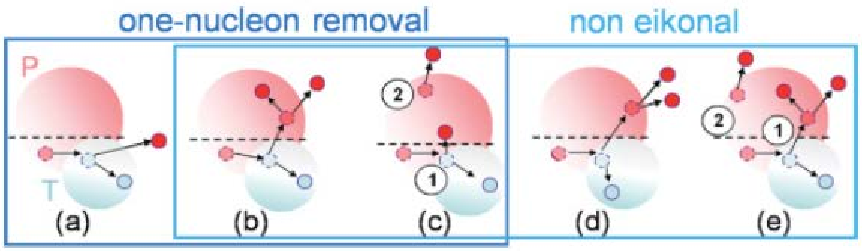


T. Aumann *et al*., PRL. **84**, 1999(2000).
F. Flavigny *et al*., PRL 108, 252501 (2012).

Knockout Reaction--INC Description

Intranuclear Cascade Model

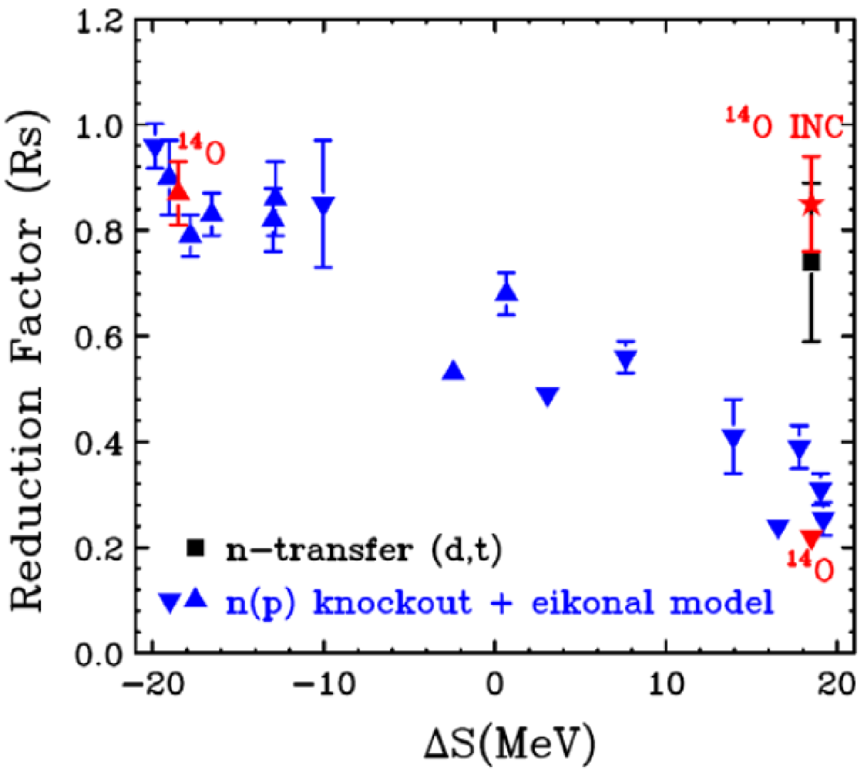
INC: Direct knockout +
multiple scattering + core excitation



$$\sigma = \sigma_{\rm casc}^{NN=1} + \sigma_{\rm casc}^{NN>1} + \sigma_{\rm evap}$$

Proj.		ℓj	C^2S	Exp $\sigma_{\rm exp}$ (mb)	INC σ	Eikonal $\sigma_{\rm eik}$ (mb)
^{14}O	$-n$	$p_{3/2}$	3.7	13.4 ± 1.4	15.8	50
^{32}Ar	$-n$	$d_{5/2}$	4.1	10.4 ± 1.3	18.3	34.6

C. Louchart *et al*., Phys. Rev. C. **83**, 011601 (2011).

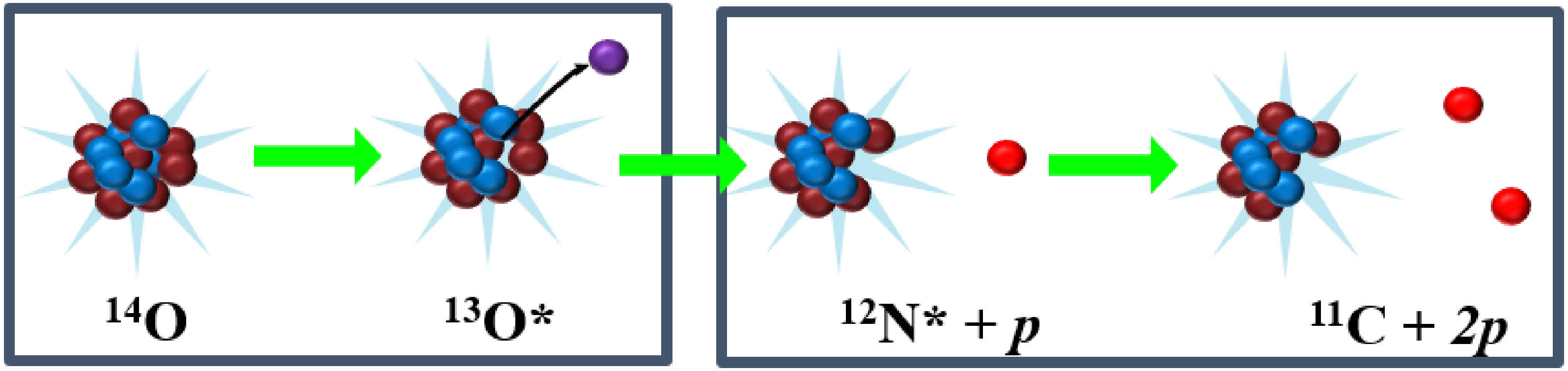


✓**Core excitation has impact on the deeply-bound nucleon removal cross section.**

→ **No experimental verification.**

Our Probe: ^{14}O Knockout Reaction with Exclusive Measurement

1) Very asymmetric.
   S_n = 23.2 MeV, S_p = 4.6 MeV, ΔS = 18.6 MeV
2) *p*-shell spherical nucleus, *ab initio* calc.
3) ^{13}N and ^{13}O have no bound excited states.



Neutron removal

"Core" Excitation + Evaporation

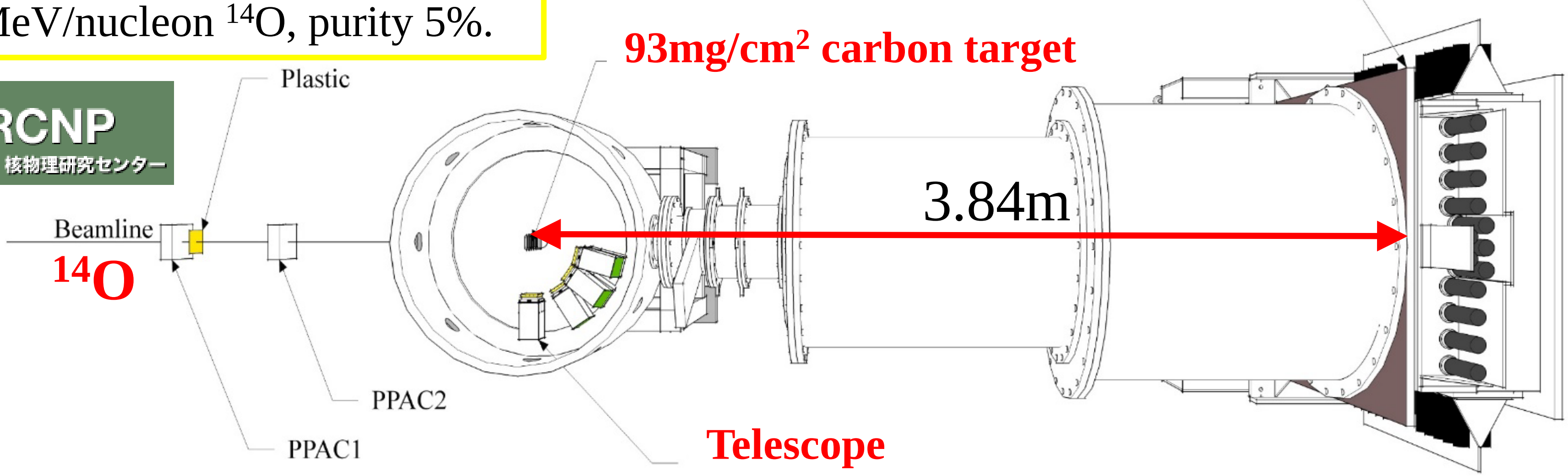
Measure excitation channels
→ Verify the contribution of "core" excitation by invariant mass technique.

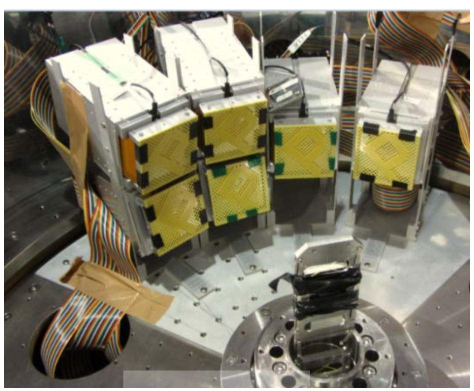
$$M = \sqrt{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{P}_i\right|^2}$$

Experimental setup

Fully Exclusive Measurements of reaction products

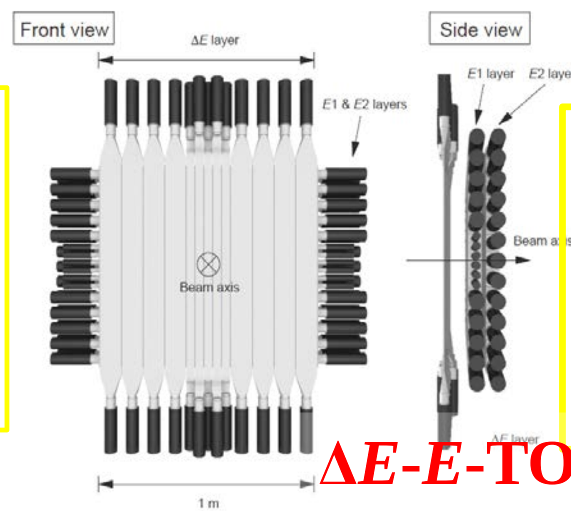
Primary beam:
80 MeV/nucleon ^{16}O
Secondary beam: 7.5×10^{3}pps
60 MeV/nucleon ^{14}O, purity 5%.





Δ*E*-*E*

6 Telescope:
10~90°, each contains DSSD+SSD+ 4*CsI.



Δ*E*-*E*-TOF

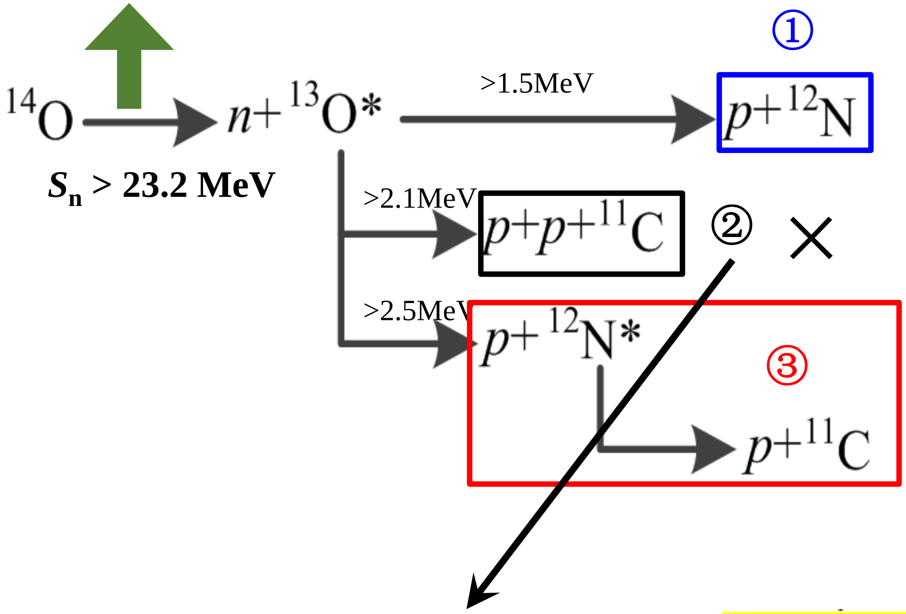
Hodoscope: 0~7°, active area 1×1 m^2, 5-mm Δ*E* and two 60-mm *E* (*E*1, *E*2) plastic scintillators.

Experimental setup

Detection efficiency (Hodoscope)

$$\sigma_{//}^2 = \sigma_0^2 \frac{A_F(A_P - A_F)}{A_P - 1}$$ Goldhaber

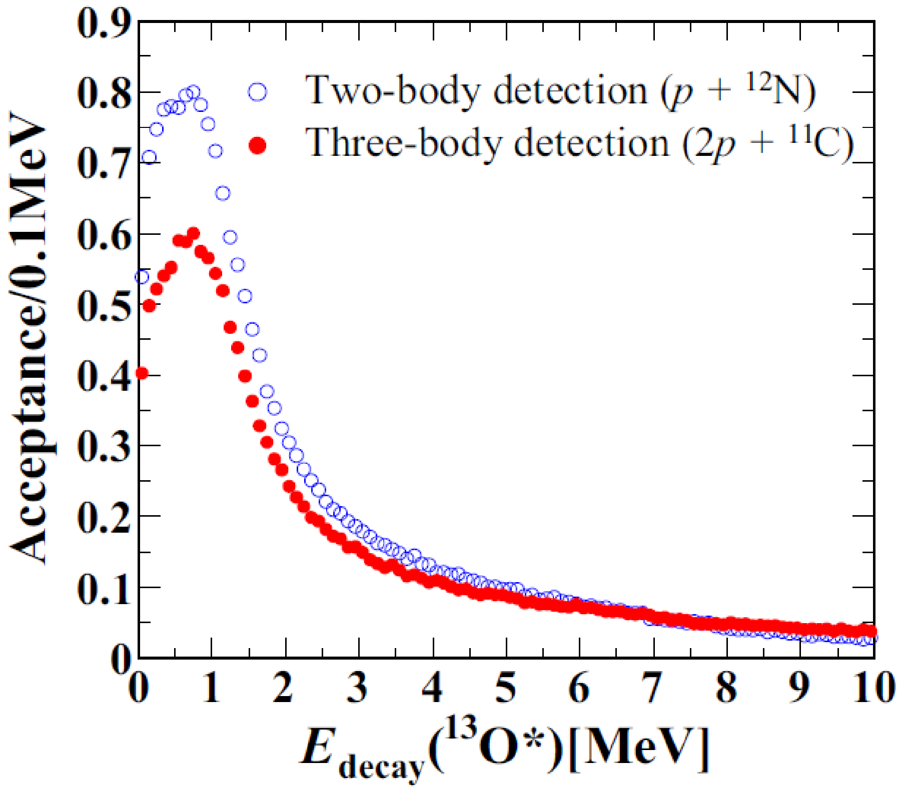
$$\frac{v_F}{v_P} = \sqrt{1 - \frac{B_n(A_P - A_F)}{A_F E_P}}$$ Borrel



(proton) channel for the decay of the resonances. The 2*p* decay to the ^{11}C ground state is also possible (Fig. 1). However, due to unfavorable penetrability, this decay route is at least 1000 times less probable than one-proton decay. Therefore

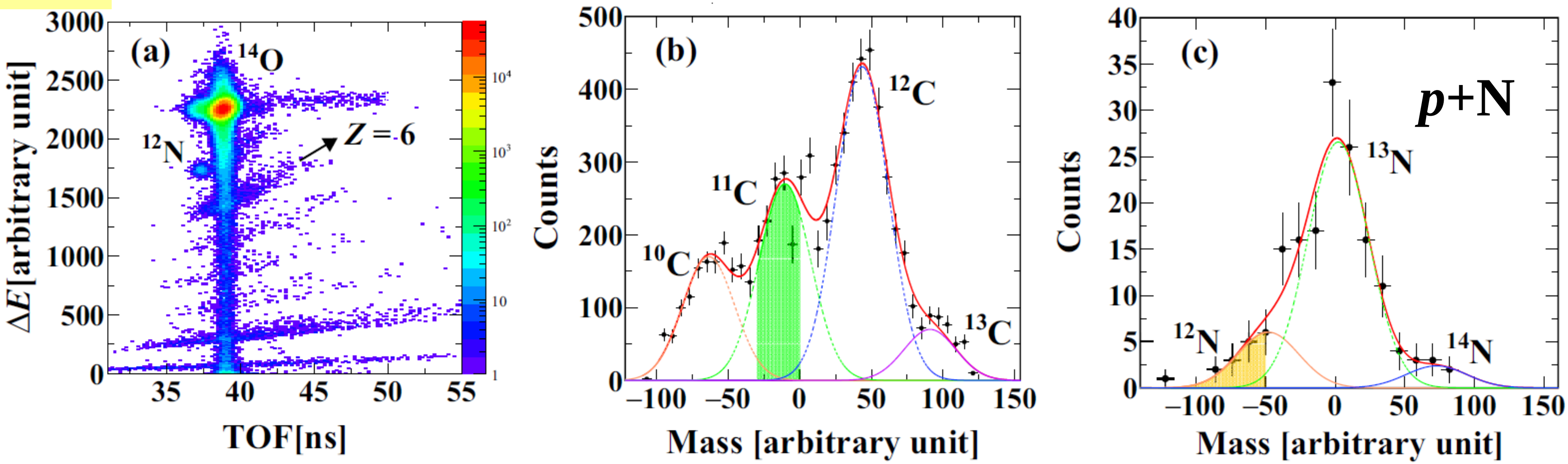
B. B. Skorodumov *et al.*, PRC75, 024607 (2007)

Knockout + Phase-space decay



Experimental results

PID



$$\sigma = \frac{R_s'}{R_i' * 1/F * N_s * (1-R_{^{11}C})}$$

$$\left(\frac{\delta_\sigma}{\sigma}\right)^2 = \left(\frac{\delta_{R_s'}}{R_s'}\right)^2 + \left(\frac{\delta_{R_i'}}{R_i'}\right)^2 + \left(\frac{\delta_{1/F}}{1/F}\right)^2 + \left(\frac{\delta_{N_s}}{N_s}\right)^2 + \left(\frac{\delta_{R_{^{11}C}}}{R_{^{11}C}}\right)^2$$

14.3%	0.2%	0.06%	0.4%	2%

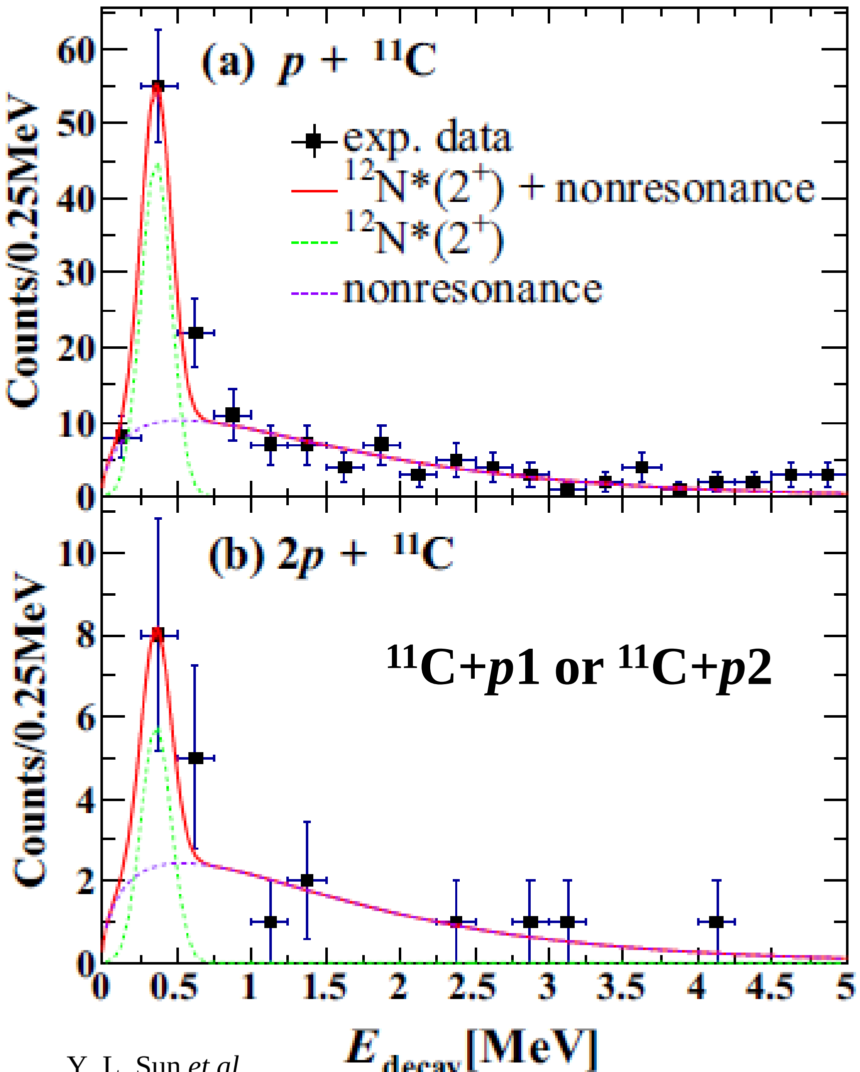
- **Cross section of 2*pn* removal to ^{11}C is 60(9) mb.**
  41(6)mb at 305MeV/nucleon, Z. Y. Sun *et al*, PRC90,037601(2014)
- **3.5 times larger than the (^{14}O, ^{13}O) channel (~16.8 mb).**

◆ **Core excitations or other complicated reaction processes ?**

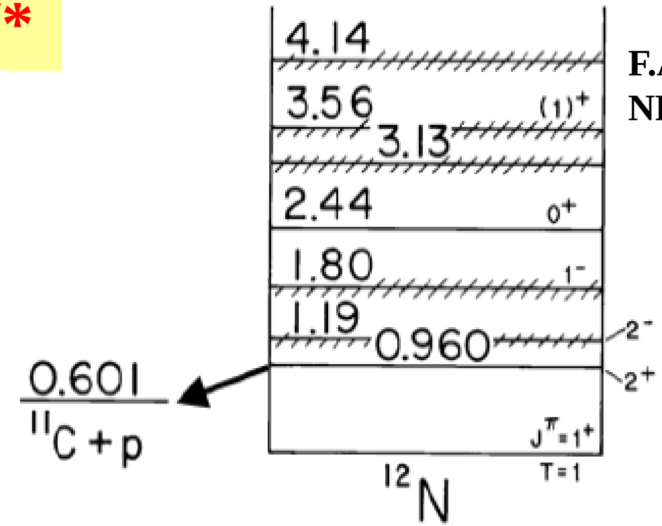
→ **To determine the excitation strength quantitatively, need coincidence with protons.**

Experimental results

Invariant mass spectrum of ^{12}N*



Y. L. Sun *et al.*,
Phys. Rev. C. 93, 044607 (2016).



F.A jzenberg-Selove, NPA 523(1991)

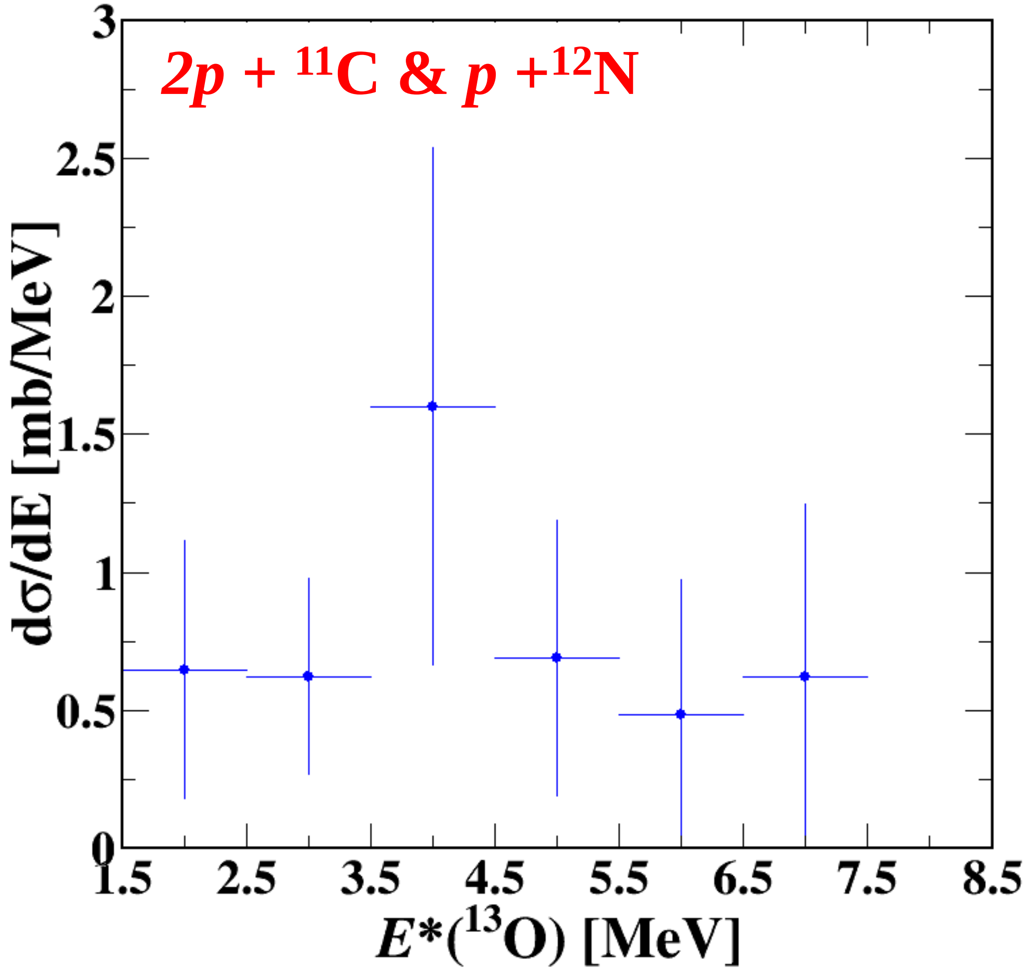
- **Crosscheck the invariant mass spectrum by ^{12}N(2+).**

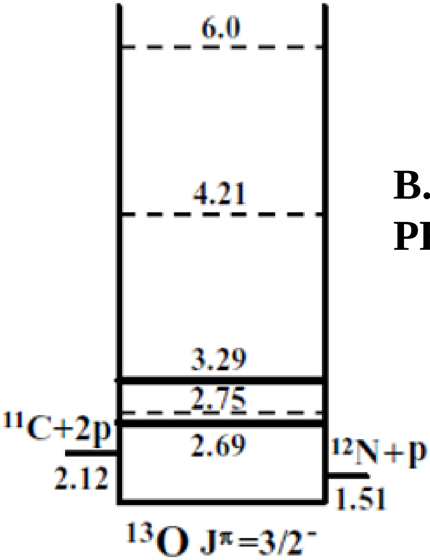
^{12}N(2+) E_{decay} = 0.36MeV
σ = 0.24(5) MeV ,
σ_{simu} = 0.19 MeV

- **Confirmation of sequential decay ($^{13}O^* \rightarrow p + ^{12}N^* \rightarrow 2p + ^{11}C$)**

Experimental results

Invariant mass spectrum of $^{13}O^*$

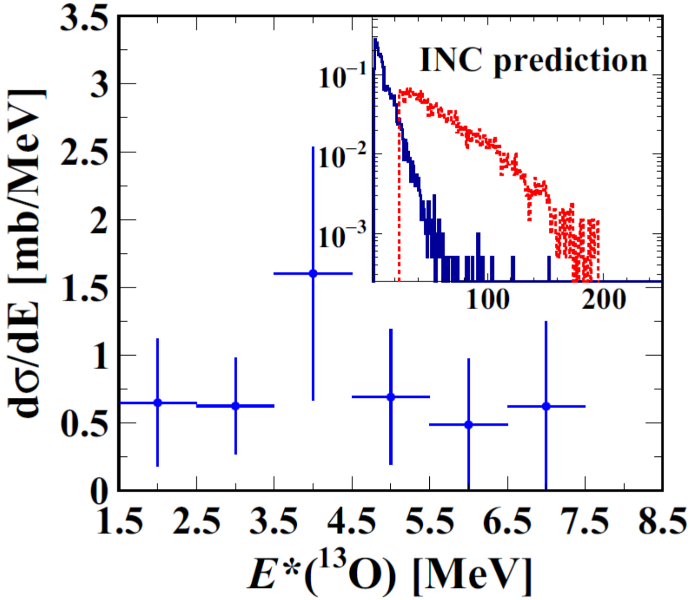




B. B. Skorodumov *et al.*, PRC75, 024607 (2007)

- **Invariant mass spectrum of ^{13}O up to $E^* < 7.5$ MeV.**
- **No obvious peaks due to the limited statistics.**
- **Suppose all of these events came form the decay of $^{13}O^*$ to get the upper limit.**

Results and discussion



◆ **The upper limit of the cross section for one-neutron removal from ^{14}O followed by proton evaporation was extracted.**

→**First constraint on the role of core excitation and evaporation processes**

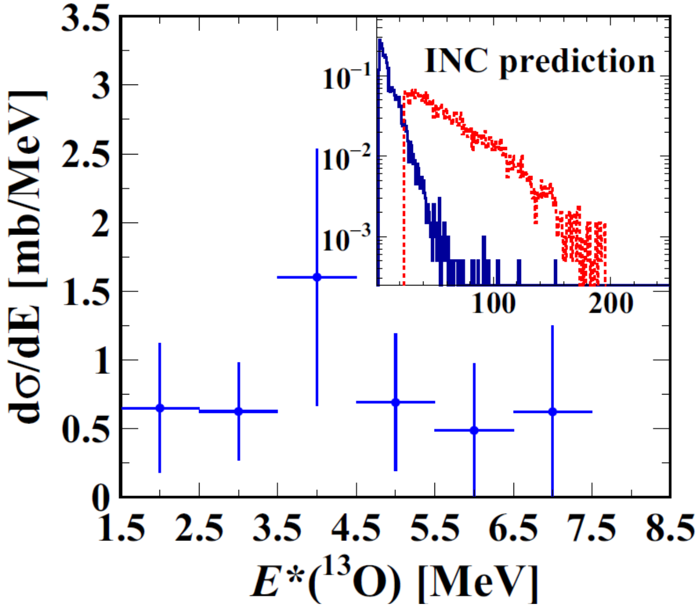
→**INC predictions are within the limits.**

Exit channels	σ_{expt} [mb]	σ_{INC} [mb]	σ_{eik} [mb]
^{13}O	16.8(12)[a]	13	57.6
^{11}C	60(9)	66	Not applicable
$^{13}O^* \rightarrow p + {}^{12}N$	<2.0(14)[b]	0	
$^{13}O^* \rightarrow 2p + {}^{11}C$	<2.6(14)[b]	2.5	
$^{13}O^* \rightarrow$ others	Not measured[c]	3.7	

a) Deduced from previous measurement in PRL, 108, 252501 (2012).
b) For unbound excited states of ^{13}O below 7.5 MeV.
c) Limited by the geometric acceptance previous measurement

Y. L. Sun *et al.*,
PRC. 93, 044607 (2016).

Results and discussion



- ✓ **INC, *E** up to 200MeV, no peaks**
- ✓ **Don't explicitly contain structure information**
- ✓ **Cannot be used to extract SF**

→Comparable strength between (^{14}O, ^{13}Og.s.) and (^{14}O, $^{13}O^*$)

Exit channels	σ_{expt} [mb]	σ_{INC} [mb]	σ_{eik} [mb]
^{13}O	16.8(12)[a]	13	57.6
^{11}C	60(9)	66	Not applicable
$^{13}O^* \to p + {}^{12}N$	<2.0(14)[b]	0	
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$^{13}O^* \to$ others	Not measured[c]	3.7	

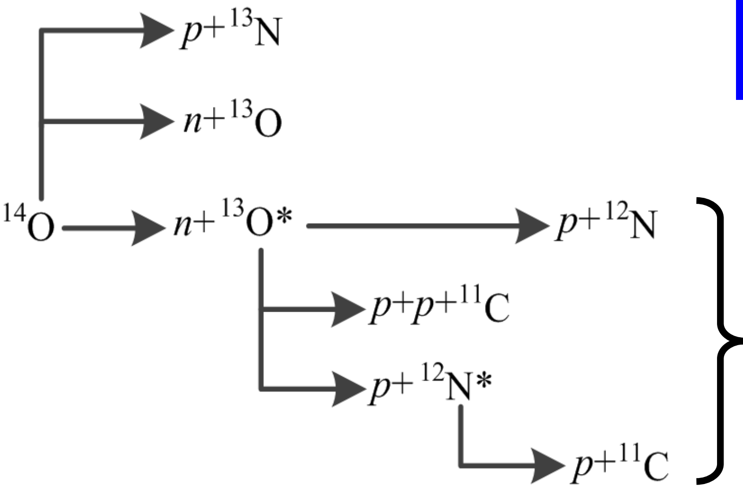
6.2 mb in total, non-direct population

a) Deduced from previous measurement in PRL, 108, 252501 (2012).
b) For unbound excited states of ^{13}O below 7.5 MeV.
c) Limited by the geometric acceptance previous measurement

Y. L. Sun *et al.*, PRC. 93, 044607 (2016).

discussion

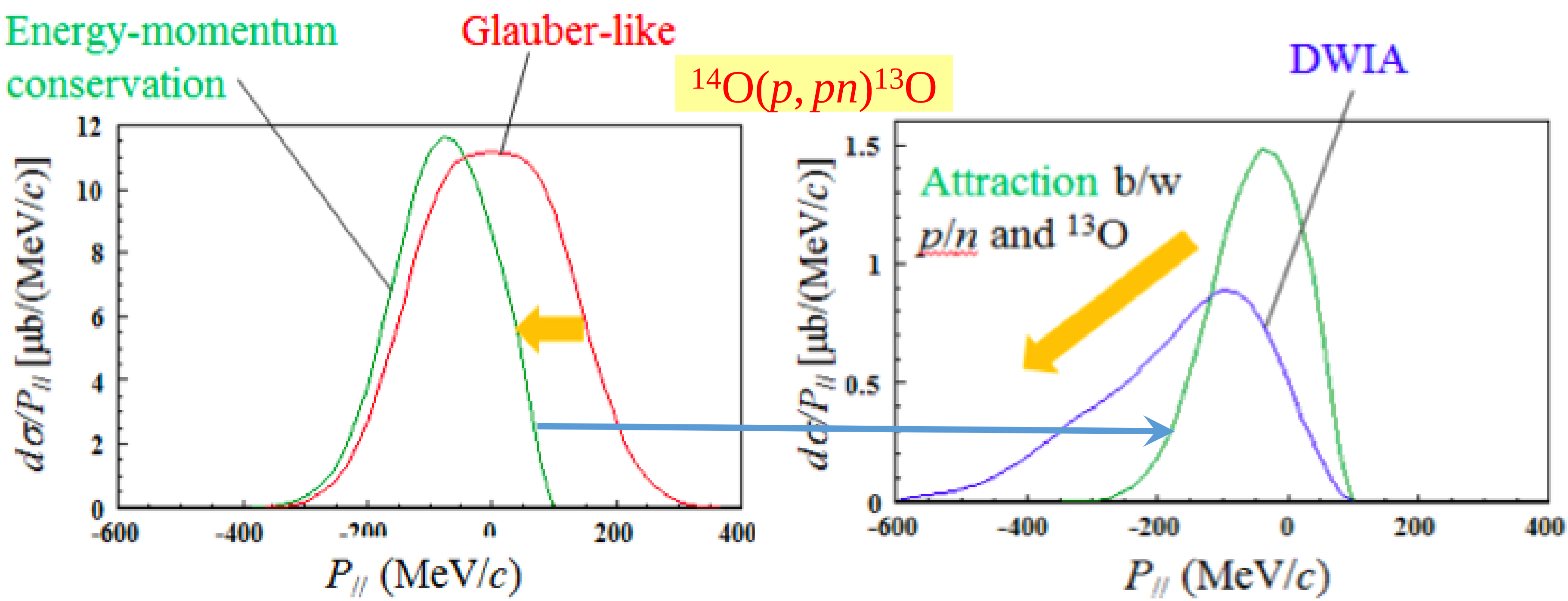
- ✓ INC cannot be used for spectroscopic study
- → Modification of eikonal model ?
- → CDCC continuum up to high excited states ?



$$S(b) = \exp[i\chi(b)], \quad \text{with } \chi(b) = -\frac{1}{\hbar v}\int_{-\infty}^{\infty} dz\, U_{\text{opt}}(r),$$

Imaginary part ?

- ✓ Use proton target for Spectroscopic study ?



K. Ogata *et al.*, Phys. Rev. C 92, 034616 (2015).

Summary

- ✓ Exclusive measurement of 60 MeV/nucleon ^{14}O beam on a carbon target was performed at RCNP.

- ✓ The unbound excited states of ^{13}O were reconstructed by using the invariant mass method.

- ✓ $\sigma(^{14}O, ^{11}C)=60(9)$ mb, which is 3.5 times larger than the deduced one-neutron-removal cross section of 16.8(12) mb.

- ✓ $\sigma(^{14}O, p+^{12}N/2p+^{11}C) < 4.6(20)$ mb, with $E^*(^{13}O) < 7.5$MeV.
  $\sigma(^{14}O, ^{13}O^*)_{INC} = 6.2$mb, for the non-direct population of unbound $^{13}O^*$.

- ✓ The data provide first constrain on the role of core excitation and evaporation process in deeply bound nucleon removal.

- ✓ The consistency with INC indicates that, non-direct reaction processes play an important role in the deeply bound nucleon removal from asymmetric nuclei at intermediate energies.

Thank you!

RIEKN
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Thank you very much for your attention !