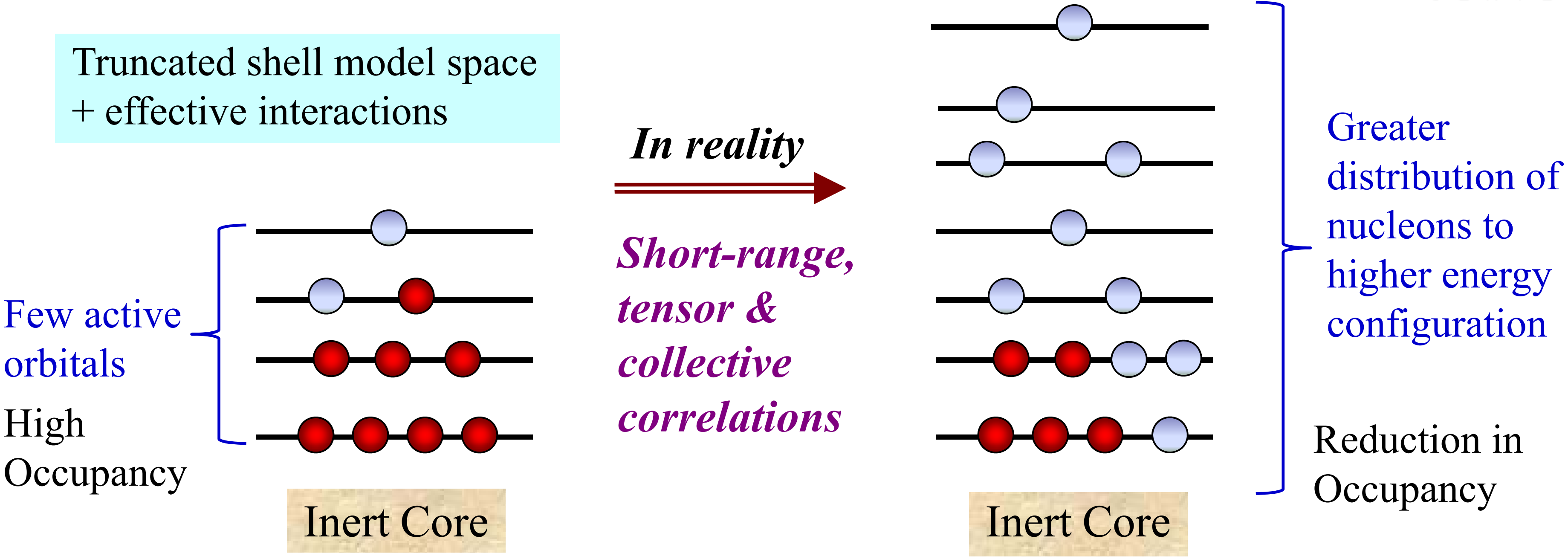
Nucleon Correlations using Direct Reactions

Truncated shell model space
+ effective interactions



Few active orbitals

High Occupancy

Inert Core

In reality

Short-range, tensor & collective correlations

Greater distribution of nucleons to higher energy configuration

Reduction in Occupancy

Inert Core

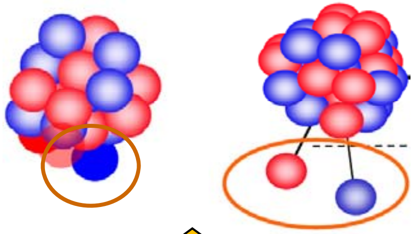
Probing the nuclear wave function

Removing nucleon(s) from occupied orbital
→ ***Cross sections (probability)*** depend on the single-particle occupancy & ***overlap*** of many-body wave functions

Full Knowledge of Correlations → Complete Understanding of Nuclear Properties

Nucleon Correlations using Direct Reactions

Spectroscopic Overlaps



Cross Section Measurements Coupled with Reaction and Structure theories

Reaction Model : Interface between Observables ↔ Nuclear Structure Knowledge

Insight ↑

Structure Input : *Microscopic info. / Wave functions & Overlaps* ⇒ **Reaction Model** → **Calc. Cross Sections**

⇕

Expt. Cross Sections

↑ **Nature**

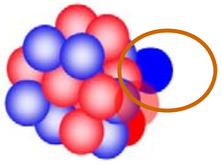
GOAL: Established Framework
→ Quantitative + Systematic Studies

Experimentalists + Theorists go hand-in-hand !

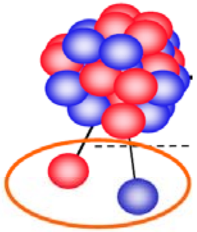
Outline

Systematic Framework – Quantitative Knowledge of Correlations
(structure & dynamics of many-body system)

Tools: Transfer & Knockout Reactions

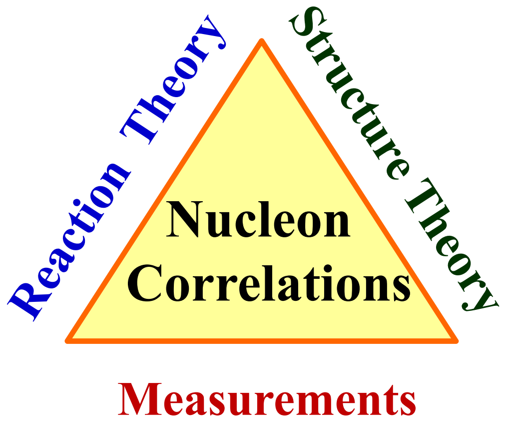


Spectroscopic Factor



Two-nucleon Overlap

Systematic Framework



Reaction Theory

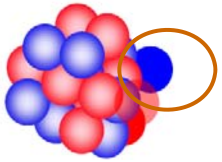
Structure Theory

Nucleon Correlations

Measurements

- **What we have learned from Direct Reactions**
- **Next Steps for Complete Knowledge & towards Goals**
- **Needs of Theory Support**

Diff. Sensitivity → Collective (longer) / Tensor / Short-range Correlations



Spectroscopic Factor (SF)

Cross Sections + Reaction Model

→ Spectroscopic Factors (expt)

Quantify Occupancy → Correlation Effects

How good the effective interaction in Shell Model can describe the correlations ?

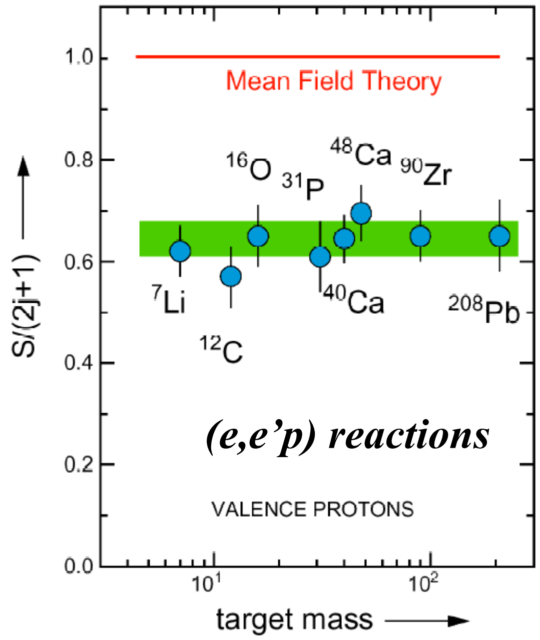
$$SF_{\exp}/SF_{SM}=1$$

SM description is accurate

$$SF_{\exp}/SF_{SM}<1$$

Some correlations missing in the interactions ?

How much ? What is the Isospin Dependence of nucleon correlations?



(e,e'p) – Stable nuclei (near closed shell)

- ***Constant ~30-40% of SF reduction compared to theory***
- ***Correlations missing in shell-model interactions***

L. Lapikas, Nucl. Phys. A553, 297c (1993)

How about Transfer Reactions ?

Transfer Reactions -- long history (>50 years)
→ abundant data, but Problems in SF(expt) !

Experimental SF from Transfer Reactions

$$SF = \left(\frac{d\sigma}{d\Omega}\right)_{EXP} / \left(\frac{d\sigma}{d\Omega}\right)_{Theo}$$

ADWA (consistent set)

✓ *Johnson-Soper (JS) Adiabatic Approximation takes care of d-break-up effects*

✓ *Use global p and n optical potential with standardized parameters (CH89)*

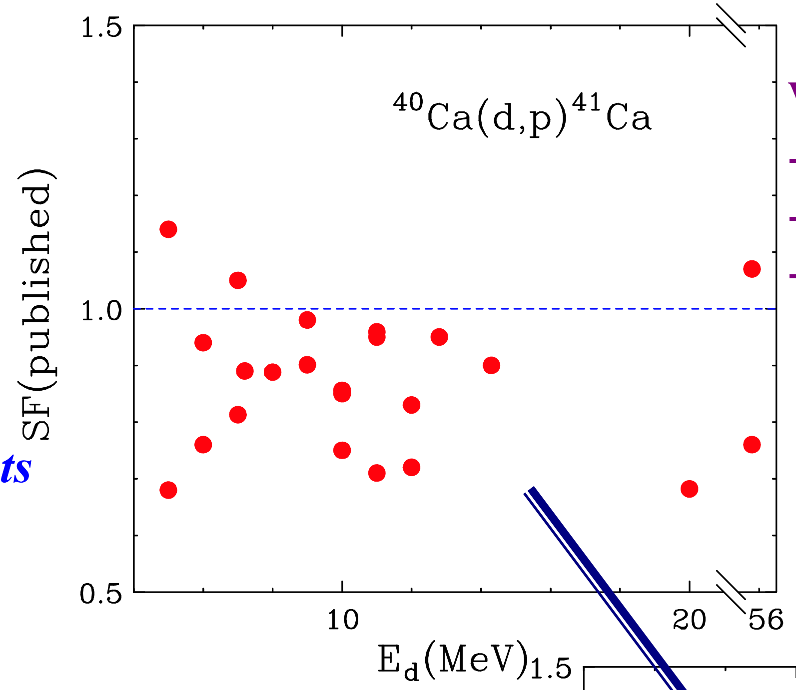
✓ *Include finite range & non-locality corrections*

✓ *n-potential : Woods-Saxon shape r_o=1.25 & a_o=0.65 fm; depth adjusted to reproduce experimental binding energy*

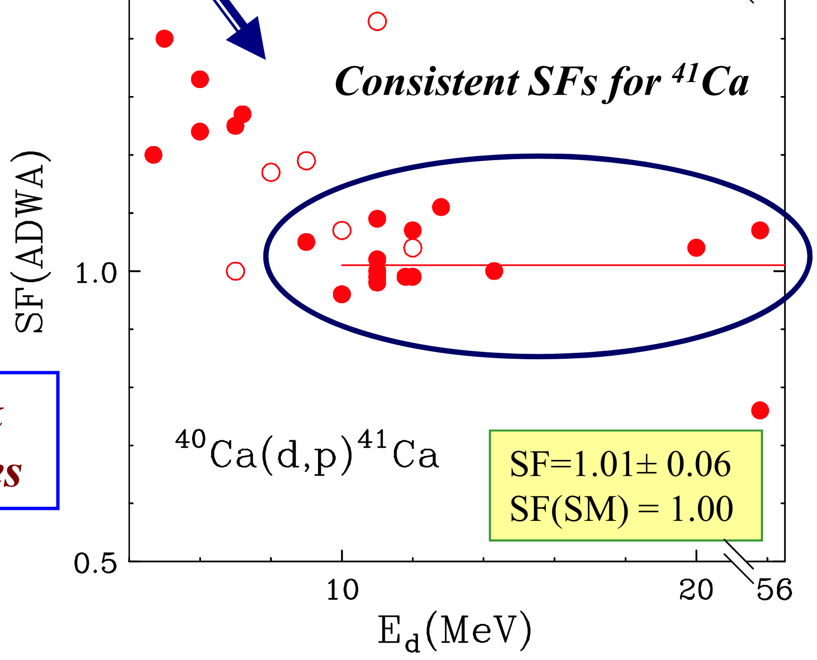
***TWOFNR**, M. Igarashi et al.,*

X.D. Liu et al., Phys Rev. C 69 (2004) 064313

J. Lee et al., Phys. Rev. C75 (2007) 064320

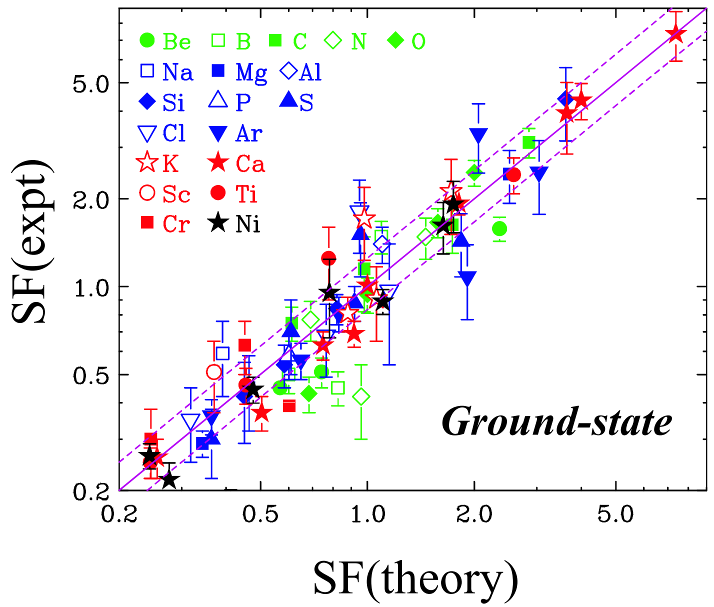


Well-known problem
- optical model potentials
- parameters
- reaction models



Reliable Framework
→ Systematic Studies

Survey of Spectroscopic Factor (Transfer Reactions)



__Extend to 88 nuclei__ (ground-state) :

Found 225 relevant papers

Re-analyzed (unified model) > 430 data sets

→ Extracted 88 SF(expt)

Benchmark → 20 % agreement to theory

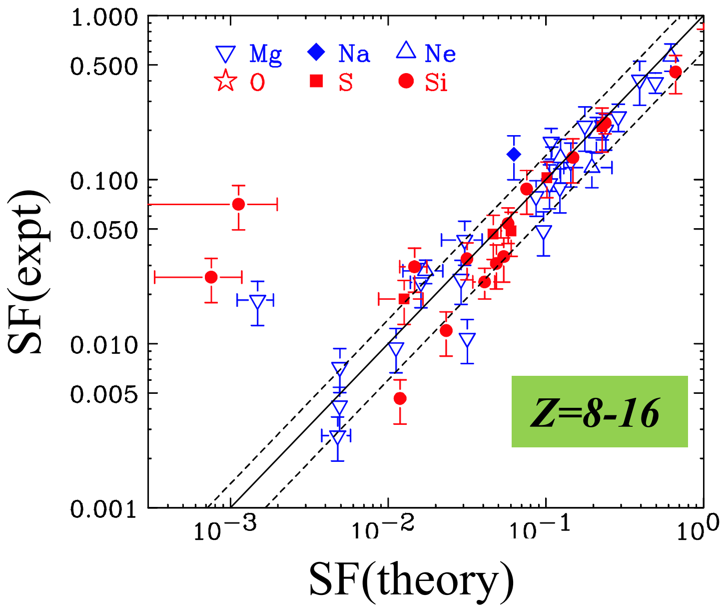
__Extend Survey to__ excited states :

Re-analyzed >2,000 data (>300 papers)

→ Extracted 565 SF(expt)

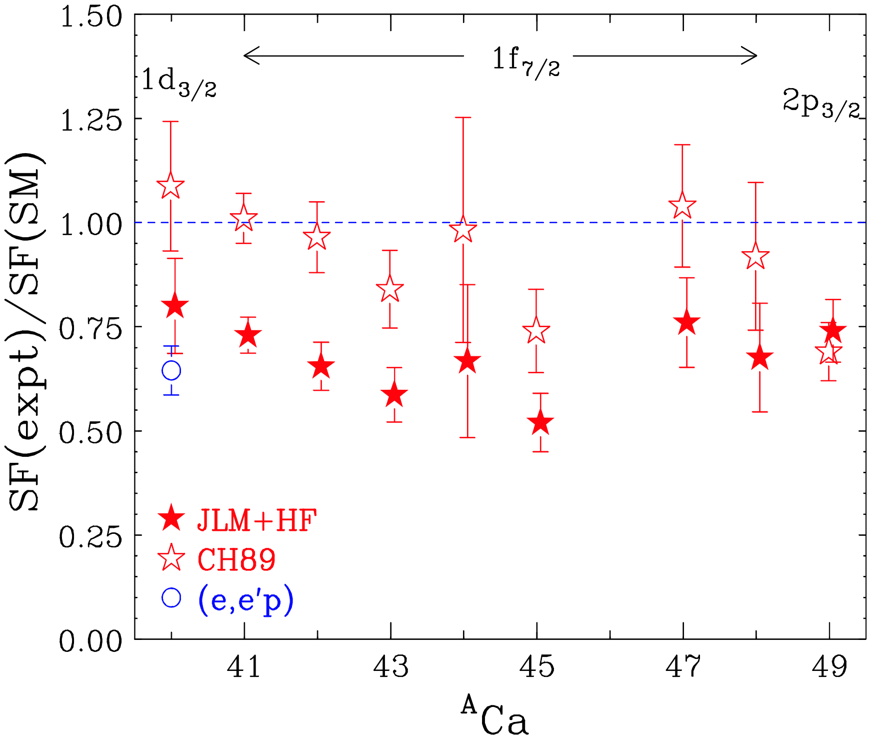
$$SF_{\exp} / SF_{theory} \approx 1$$

Do we understand all the correlations ?



M.B. Tsang, J. Lee et al., Phys. Rev. Lett 95, 222501 (2005)
M.B. Tsang, J. Lee et al., Phys. Rev. Lett 102, 062501 (2009)
J. Lee, M. B. Tsang et al., Phys. Rev. C75, 064320 (2007)
J. Lee, M. B. Tsang et al., Phys. Rev. C79, 054611 (2009)

Suppression of SFs in Transfer Reactions



Constant ~30% reduction in SFs

J. Lee et al., Phys. Rev. C 73 , 044608 (2006)

CH89 + ro=1.25 fm with minimum assumption
→ consistent SF(expt) with Shell Model

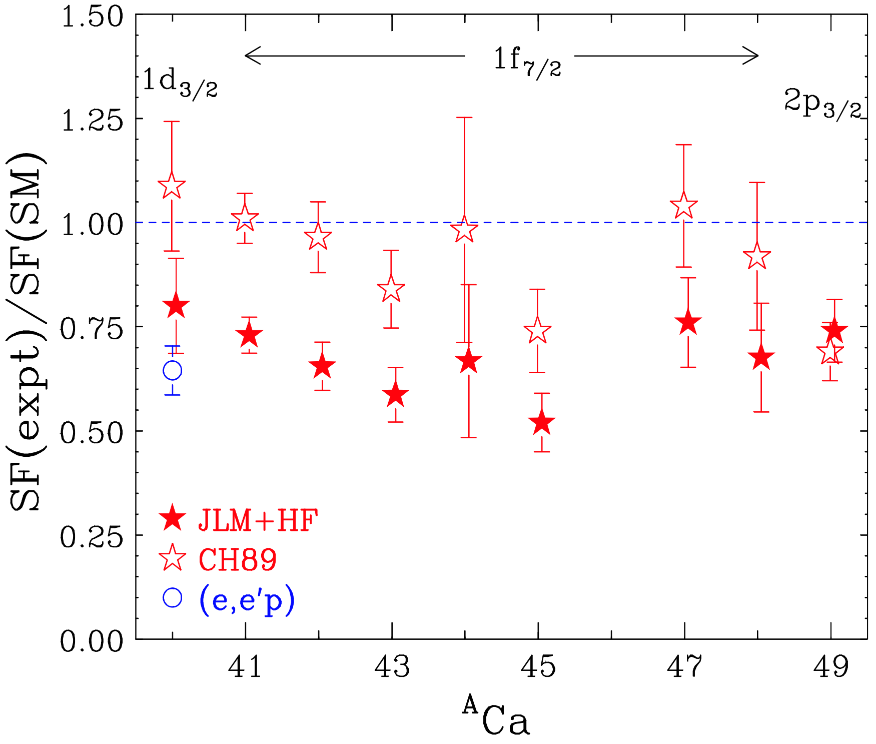
Microscopic Input in Reaction Model

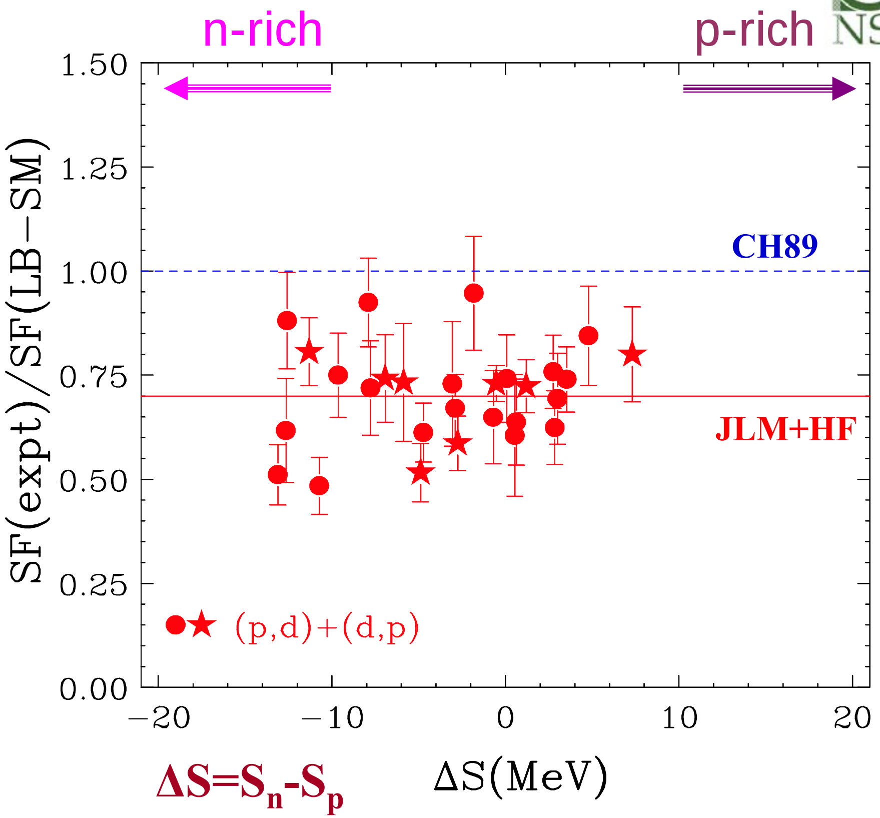
→ JLM potential & Hartree-Fock (SK20)

r_o=1.25 fm → HF rms radius

Global CH89 → JLM + HF densities

Suppression of SFs in Transfer Reactions





Constant ~30% reduction in SFs

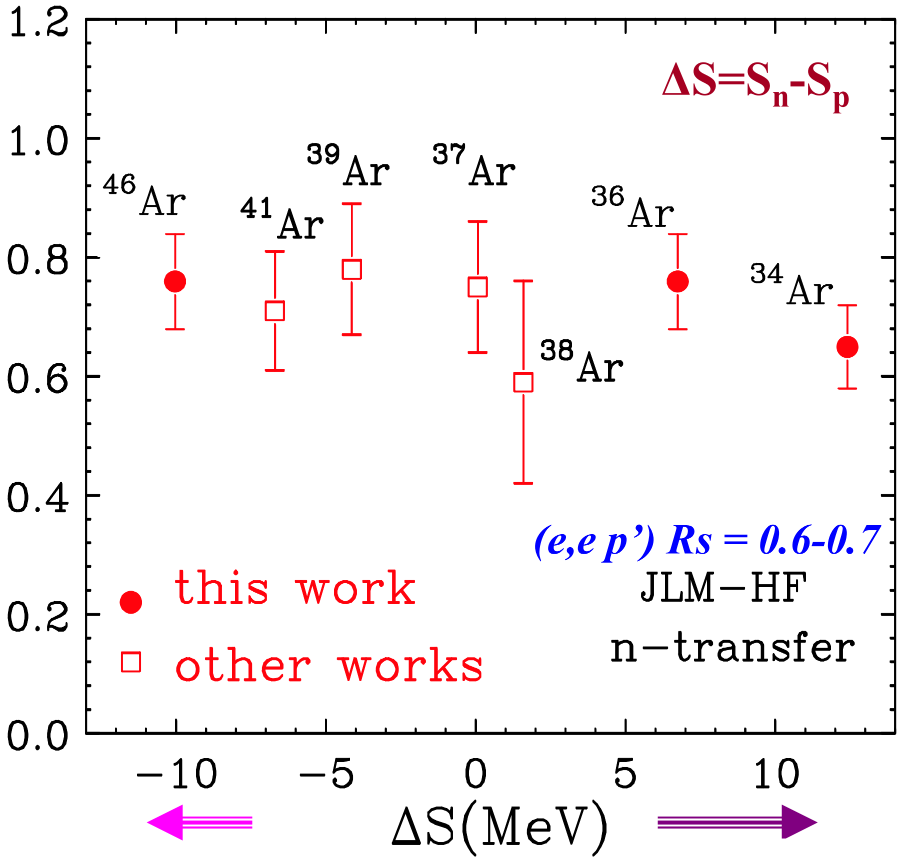
J. Lee et al., Phys. Rev. C 73 , 044608 (2006)

Different sets of consistent parameters
→ different normalizations

- ***Transfer reactions do not yield absolute SF ; Systematic approach → relative SF can be obtained reliably over a wide range of nuclei***

- ***Nuclear structure purpose → Relative normalized SFs***

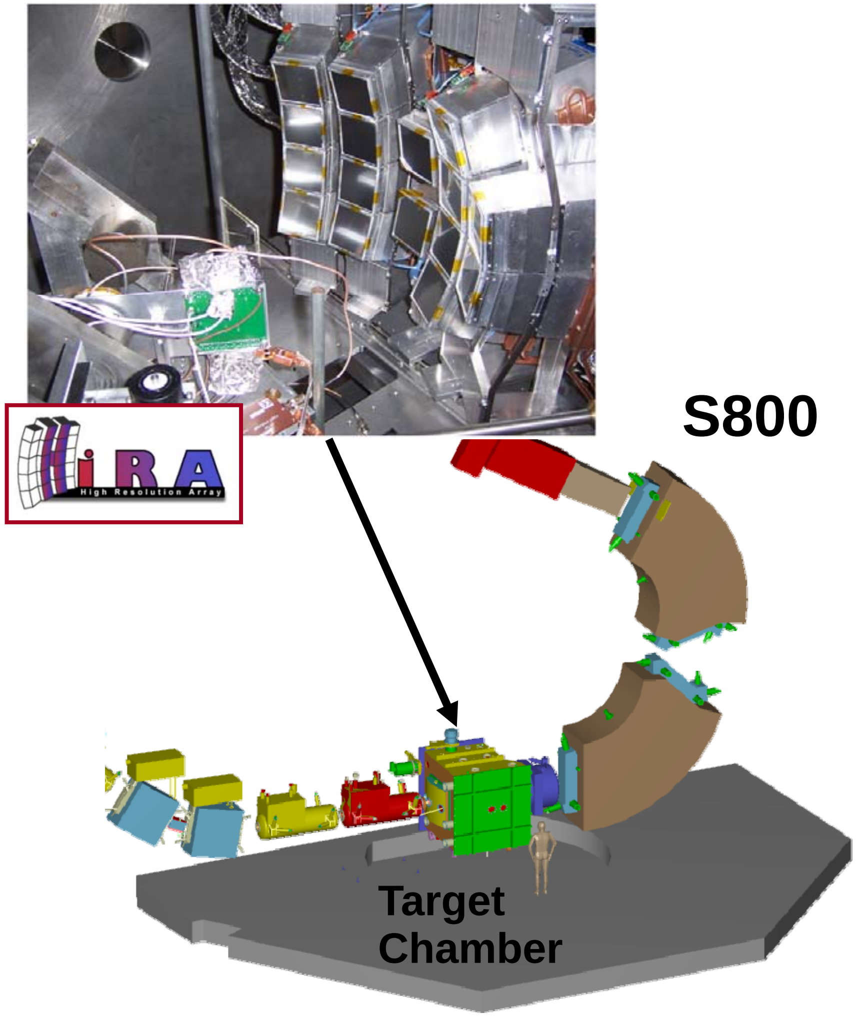
Isospin Dependence of Nucleon Correlations



Neutron-rich **Proton-rich**

$^{34,36,46}\mathrm{Ar} + p \rightarrow d + {}^{33,35,45}\mathrm{Ar}$

Inverse kinematics at 33MeV/A

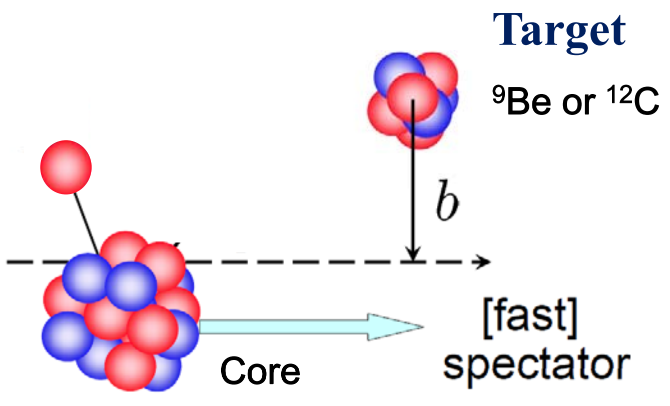


Transfer Reactions:

Weak Isospin Dependence of nucleon correlations

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

Nucleon Knockout with Fast Beams on ^{9}Be / ^{12}C Target



Projectile (fast beam)

High incident energy → Reaction only affects a nucleon at surface

Reaction Theory:
Eikonal & Sudden Approximations

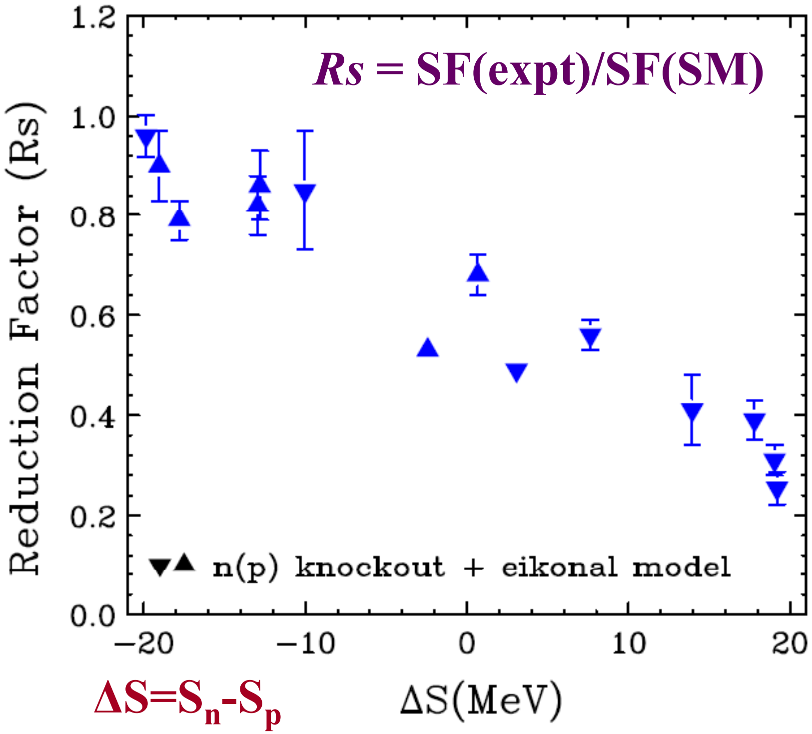
J. Tostevin et al., J. Phys. G, Part. Phys. 25, 735 (1999)

- ✓ **Large reaction cross sections (*few mb*)**
- ✓ **Thick reaction target**
- → **Powerful technique with high luminosity**

One-nucleon knockout -- away from stability

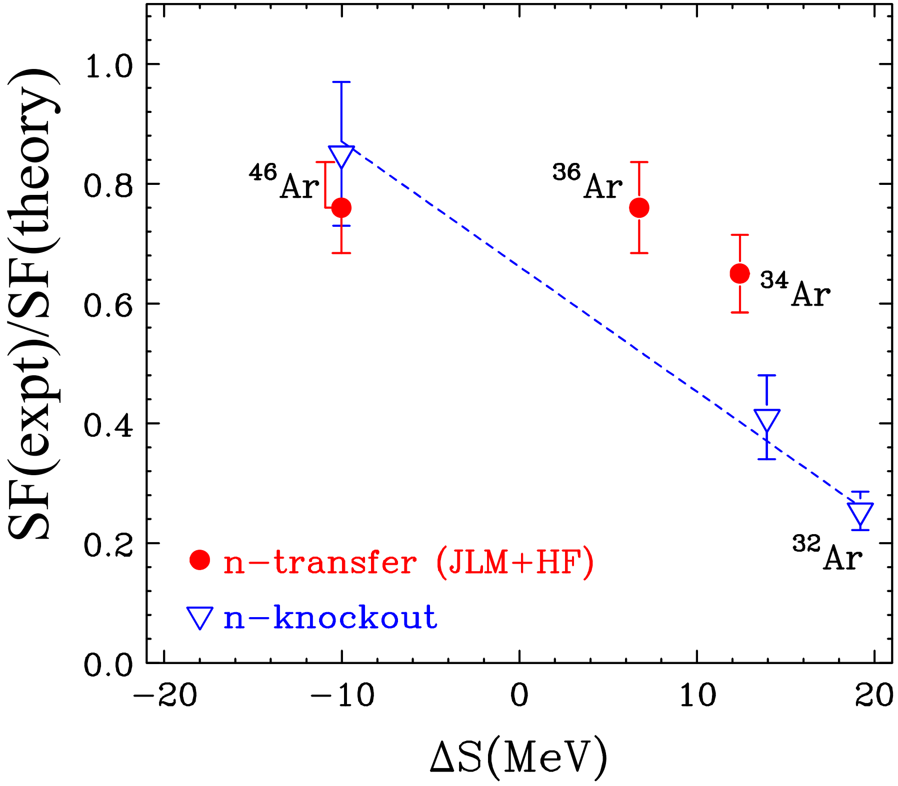
- **Rs strongly depends on separation energy**
- **More correlation effect - strongly bound valence nucleon**

A. Gade et al., Phys. Rev. C 77, 044306 (2008)
and reference therein



$\Delta S = S_n - S_p$

Isospin Dependence of Nucleon Correlations



Q: Isospin Dependence ?

Knockout reactions: Yes & Strong

A. Gade et al., Phys. Rev. C 77, 044306 (2008) & reference therein

Transfer reactions: Weak

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

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

NSCL

Systematic difference between two probes !

Incompatibility → Incomplete understanding in underlying reaction mechanism

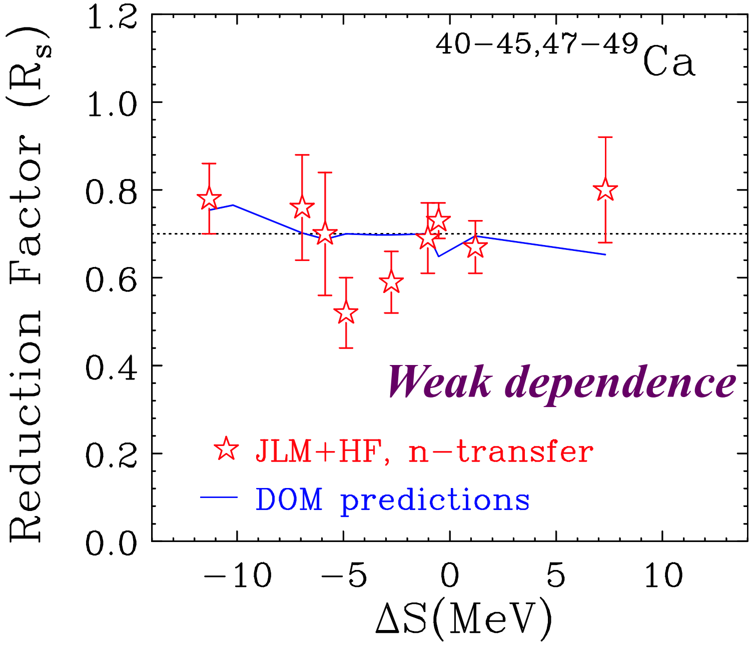
Transfer Reaction

✓ ***Future NSCL 09084: ^{34,46}Ar(p,d) at 70 MeV/A***

- same energy as knockout reactions for direct comparison

Knockout Reaction ?

Is Strong Dependence Theoretically Explaned ?



Weak dependence

Knockout reactions: Strong Dependence

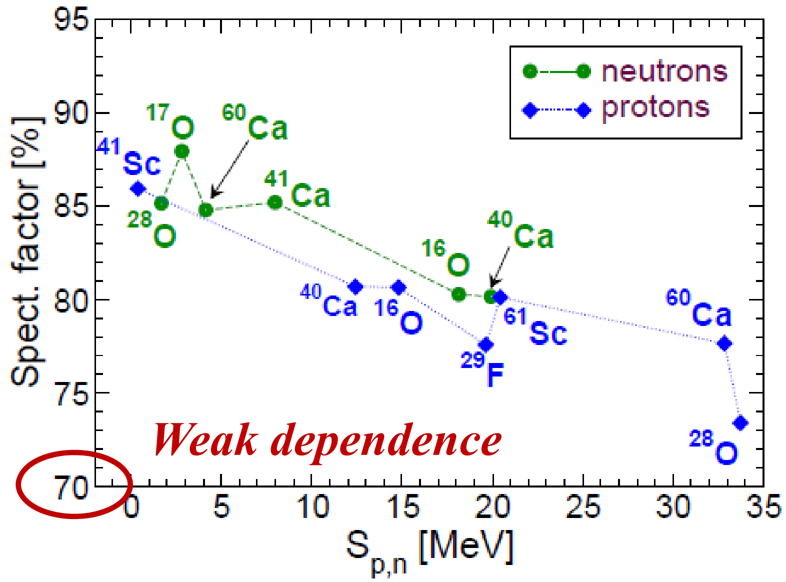
Applicability of Modal using Eikonal & Sudden approximations (core-inert) to existing knockout reaction data ?

Dispersive Optical Model (DOM)
(elastic-scattering & bound-level data for $^{40-49}$Ca)

R.J. Charity et al., Phys. Rev. C 76 , 044314 (2007)

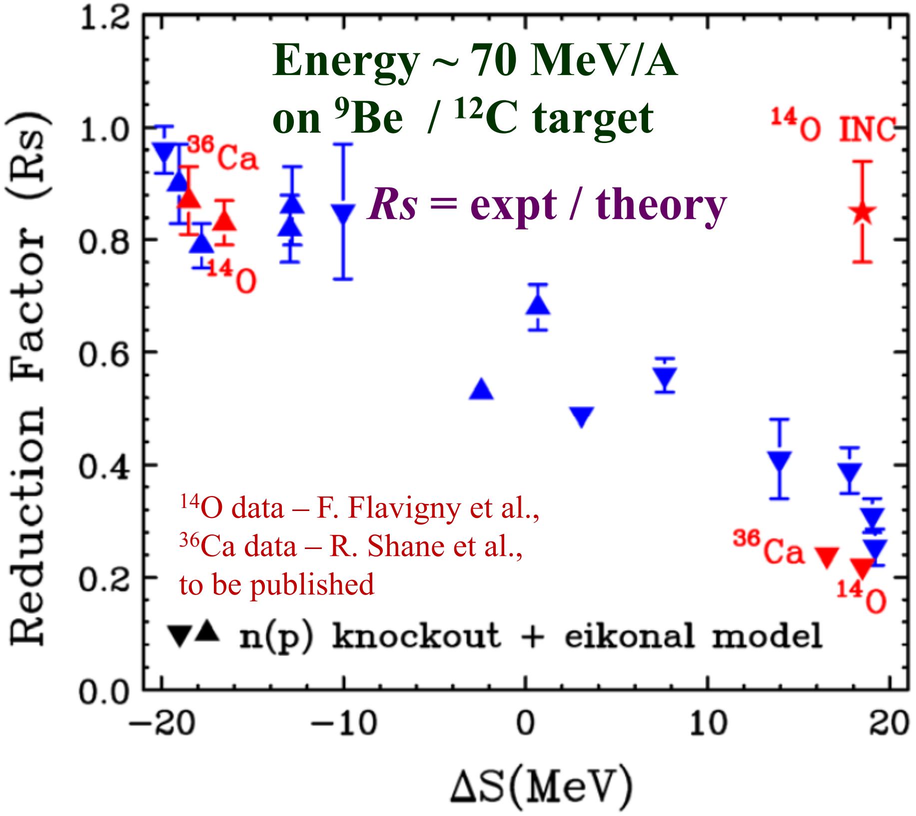
Self-consistent Green's Functions + FRPA

C. Barbieri & W. H. Dickhoff, arXiv:0901.1920v1



Weak dependence

Knockout Reaction Models



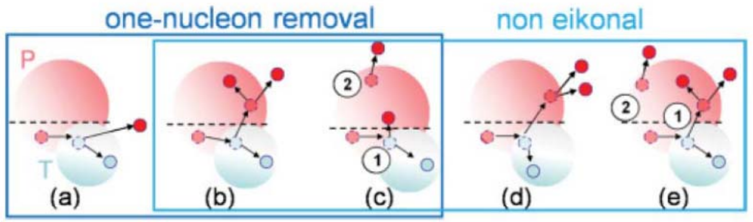
^{14}O data – F. Flavigny et al.,
^{36}Ca data – R. Shane et al.,
to be published

1. Invariant with beam energy ?

Sudden Approx - 70MeV/A high enough ?

✓ Data at energies of 200-300 MeV/A needed

2. Inert-core ? (reaction mechanism)



Direct KO | Multiple scattering/ Evaporation | Core excitation

✓ Measuring core-excitation channels → justify over-prediction due to inert-core assumption

3. (p,pN) knockout mechanism ?

"Proton" target – structure-less probe

- simpler reaction mechanism
- sensitive to larger part of wave function

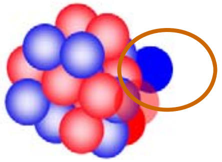
✓ Comparing physics from diff. reaction mechanisms

Intranuclear Cascade Model (*INC*)

(*with nuclear-structure input*)

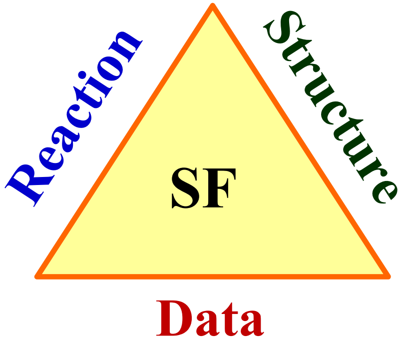
Proj.		ℓj	C^2S	$\sigma_{\rm exp}$ (mb)	$\sigma_{\rm casc}$	$\sigma_{\rm evap}$ (mb)	σ	$\sigma_{\rm eik}$ (mb)	δ
^{14}O	$-n$	$p_{3/2}$	3.7	13.4 ± 1.4	11.6	4.2	15.8	50	0.3
	$-p$	$p_{1/2}$	1.8	67 ± 6	22.5	31.4	53.9	41.2	1.3
^{24}Si	$-n$	$d_{5/2}$	1.7	9.8 ± 1.0	9.7	2.6	12.3	23.3	0.5
	$-p$	$d_{5/2}$	3.4	67.3 ± 3.5	24.8	19.7	44.5	65.5	0.7
^{24}O	$-n$	$s_{1/2}$	1.8	63 ± 7	34.3	4.2	38.5	51.2	0.8
^{28}S	$-n$	$d_{5/2}$	3.1	11.9 ± 1.2	12.6	3.2	15.8	33.2	0.5
^{32}Ar	$-n$	$d_{5/2}$	4.1	10.4 ± 1.3	11.2	7.1	18.3	34.6	0.5

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



Needs of Reaction Theory Support

Single-particle Overlap (SF)



Transfer Reactions:

✓ DWBA + adiabatic approach
○ Assess uncertainties in reaction models
○ Check reliability for high-energy transfer
○ Extend optical model potential to exotic nuclei

^{9}Be or ^{12}C-induced Knockout Reactions:

✓ Surrey-Reaction Model (J.A. Tostevin (Surrey))
✓ Intra-Nuclear Cascade Model (F. Flavigny (CEA Saclay))
○ Another Reaction model (K. Minomo, M. Yahiro (Kyushu Univ.))
○ Check energy dependence
○ Include core-breaking effects for deeply-bound nucleon removal

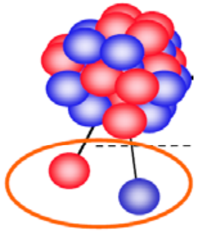
Proton-induced *(p,pN)* Knockout Reactions:

✓ CDCC calculations (T. Matsumoto (Hokkaido Univ.))
✓ DWIA calculations (S. Kawase (CNS) code:THREEDEE)

Model → carbon-induced & proton-induced reaction on the same footing

○ Future work (K. Minomo (Kyushu Univ.))

Two-nucleon Overlap



Two-like nucleon Transfer Reaction

Similarity between pairing field and 2-body transfer operator

Two-nucleon transfer reactions like (t,p) or (p,t) → specific tool to probe T=1 pair correlations

Ground-state composed of BCS pairs, two-nucleon transfer cross sections enhanced

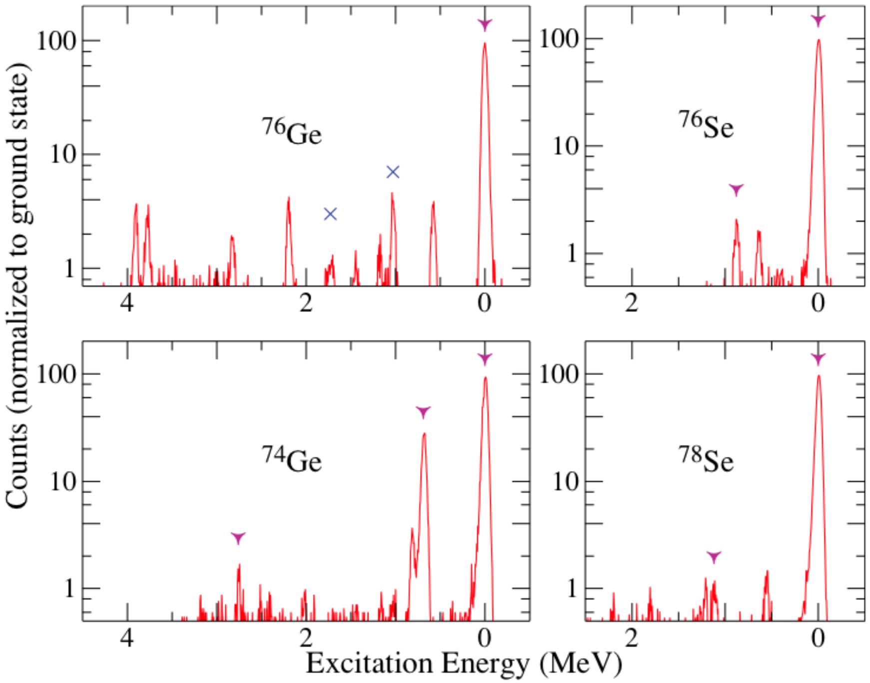
R.A. Broglia et al., Adv. Nucl. Phys. 6, 287 (1973)

^{76}Ge & ^{76,78}Se(p,t) strength: predominately to the ground states → simple BCS paired states

How to get more quantitative + systematic knowledge of *nn-pairing ?*

Spectra from (p,t) reactions

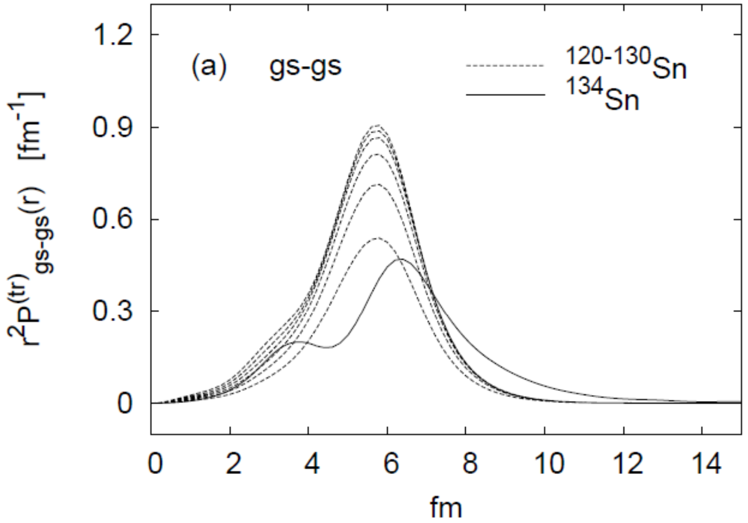
S.J. Freeman *et al*. PRC **75** 051301(R) (2007)

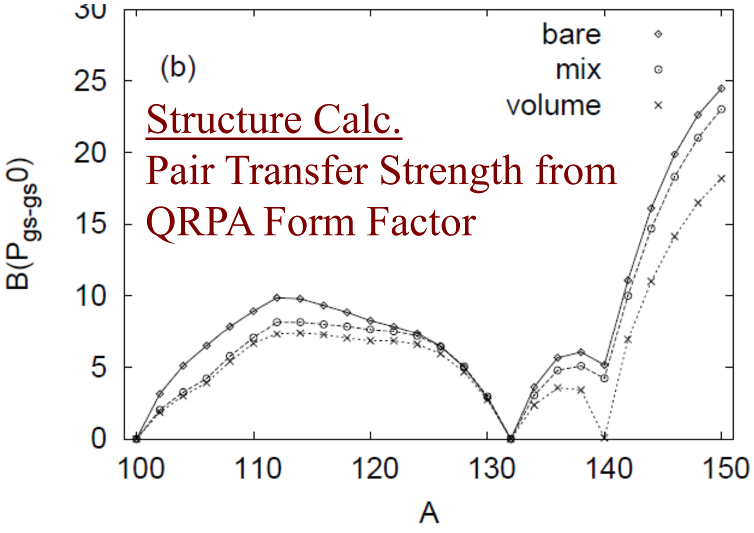


nn-pairing in *Sn* Isotopes

Pair Transition density – Skyrme HFB + QRPA approach

M. Matsuo et al., PRC 82, 024318 (2010)

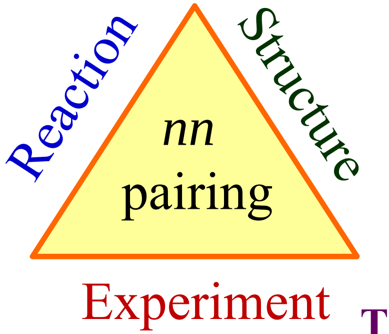




Structure Calc.

Pair Transfer Strength from QRPA Form Factor

How to see & interpret these *nn*-pairing structure in Transfer Reaction ?



Reaction

Structure

nn pairing

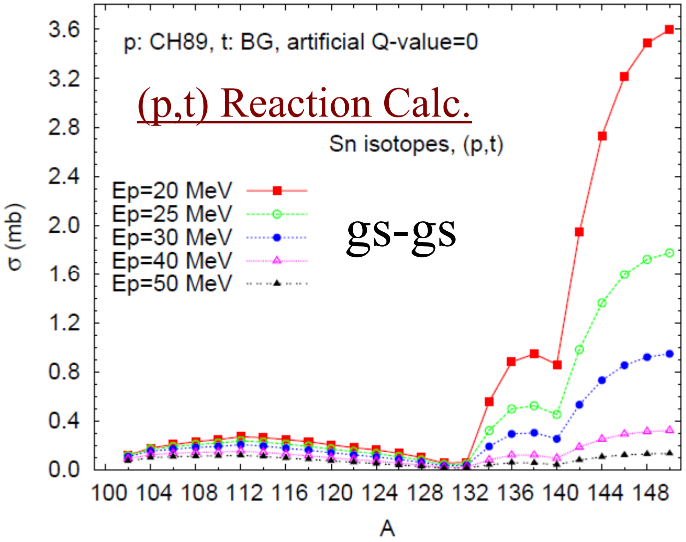
Experiment

Establish Reliable Framework by Systematic Reaction Calc.

One-step transfer + QRPA Form Factor

TWOFNR, M. Igarashi et al.,

Instruction: Y. Aoki (Tsukuba), Calc: D.Y. Pang (Peking)



(p,t) Reaction Calc.

gs-gs

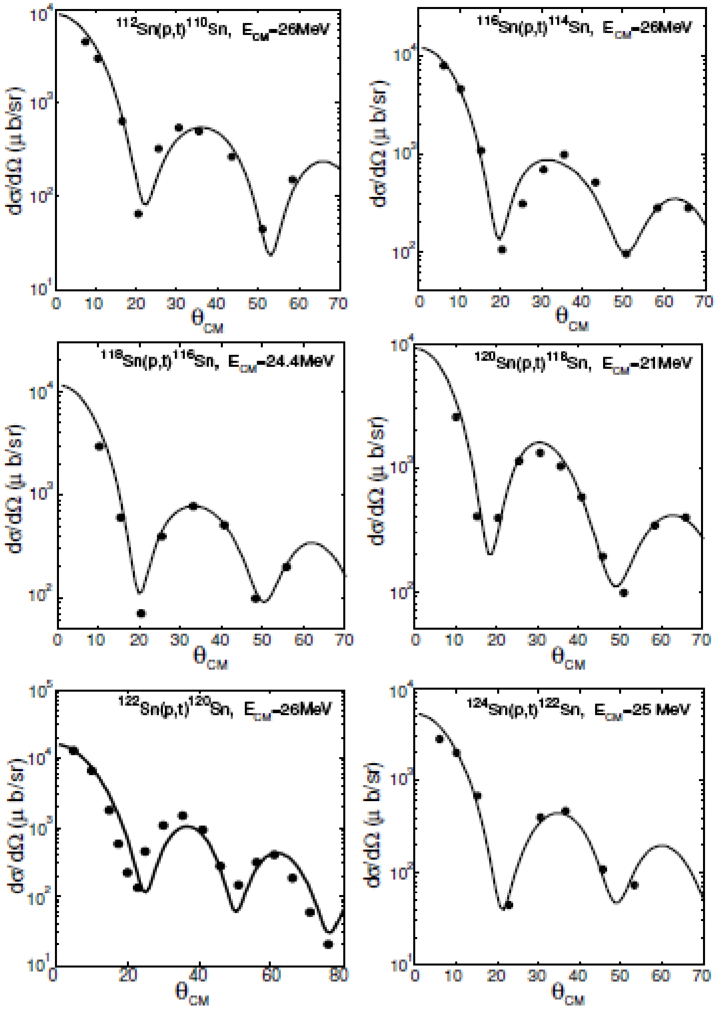
***New: (p,t)* to resonance states → Width ?**

Reaction Calc: 0_2^+ & 2_1^+ (in progress)

Advanced 2*n* Transfer Calculations

Calculation of ***absolute (p,t)*** cross sections:

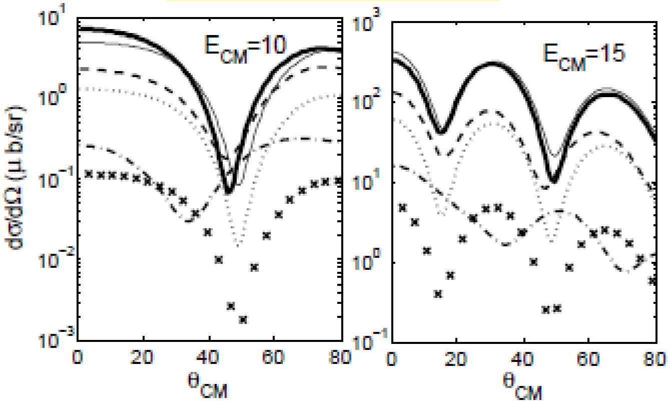
- Proper pairing interaction
- Multistep (successive, simultaneous)



G. Potel, R.A. Broglia et al., accepted by Phys. Rev. Lett

	$\sigma(\mu b)$			
	5.11 MeV	6.1 MeV	10.07 MeV	15.04 MeV
total	1.29×10^{-17}	3.77×10^{-8}	39.02	750.2
successive	9.48×10^{-20}	1.14×10^{-8}	44.44	863.8
simultaneous	1.18×10^{-18}	8.07×10^{-9}	10.9	156.7
non–orthogonal	2.17×10^{-17}	7.17×10^{-8}	22.68	233.5
non–orth.+sim.	1.31×10^{-17}	3.34×10^{-8}	3.18	17.4
pairing	1.01×10^{-19}	6.86×10^{-10}	0.97	14.04

^{132}Sn(p,t)^{130}Sn



Reaction

Structure

nn pairing

Experiment

Q1: Best reaction energy for 2N-transfer expt. ?

Energy region → large cross sections & good control of reaction mechanism (calculation).

Q2: Targets (*p*,^{6}*Li*,^{18}*O*) - mechanism described ?

Ans: from Reliable Reaction Calc.

Neutron-Proton Pair Correlations

In nuclei: 4 types of Pairs

Isovector (T=1, S=0) nn, pp, np pair

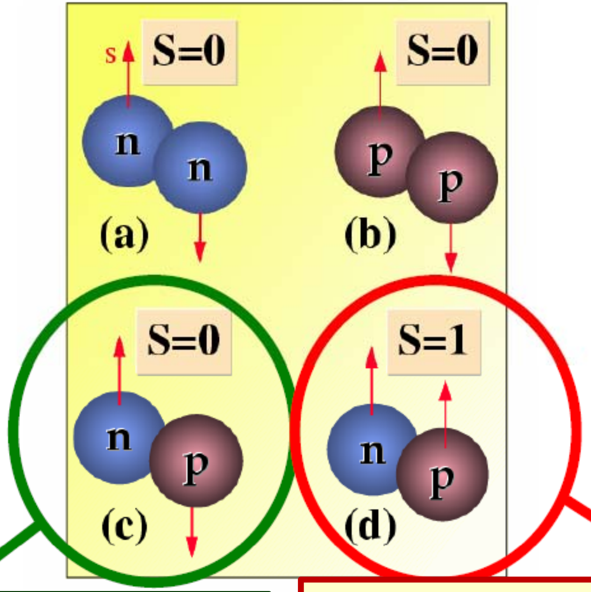
np should be similar to nn & pp

Isoscalar (T=0, S=1) np pair (deuteron-like)

→ new phase of nuclear matter

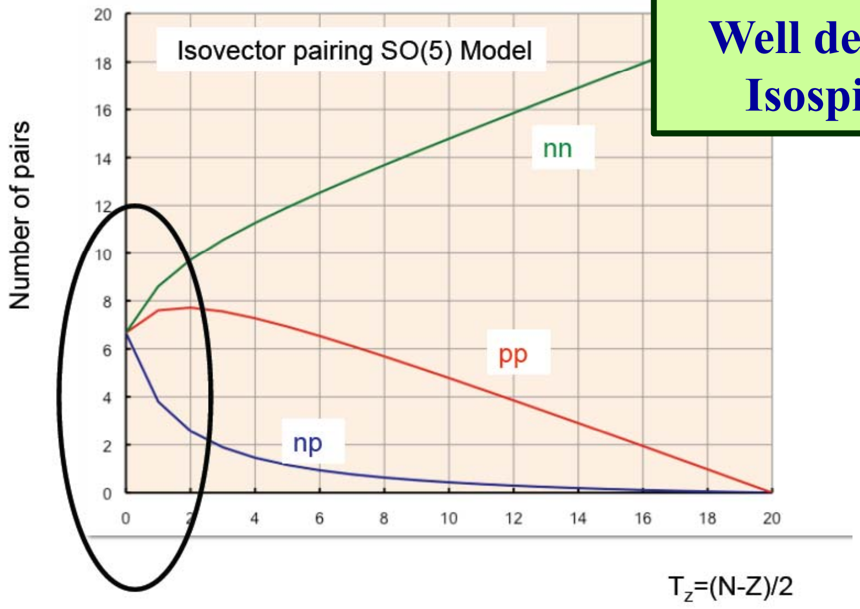
Theoretical & experimental efforts since 60's → Contradicting opinions & results !

nucleonic Cooper pairs



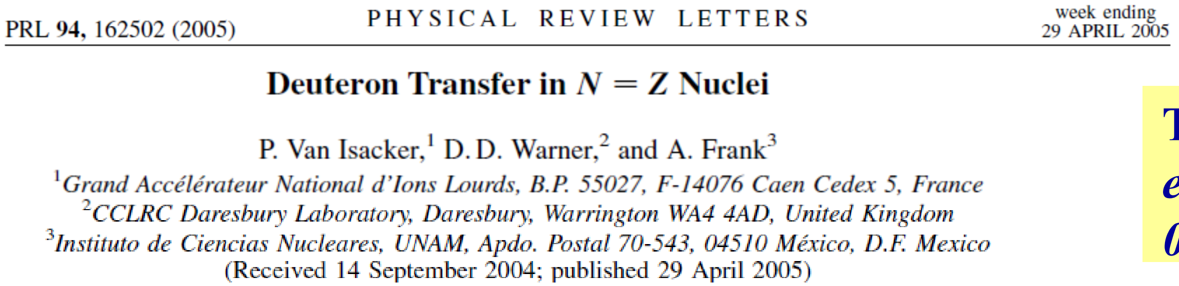
Isovector (T=1) np-pairing
Well defined from the Isospin Symmetry

Isoscalar (T=0) np-pairing
A lot of uncertainties !!



N=Z unique system for np-pairing studies !

Neutron-Proton Transfer Reactions



PRL **94**, 162502 (2005) PHYSICAL REVIEW LETTERS week ending 29 APRIL 2005

Deuteron Transfer in $N = Z$ Nuclei

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[2] *CCLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[3] *Instituto de Ciencias Nucleares, UNAM, Apdo. Postal 70-543, 04510 México, D.F. Mexico*

(Received 14 September 2004; published 29 April 2005)

Interacting Boson Model (IBM-4)

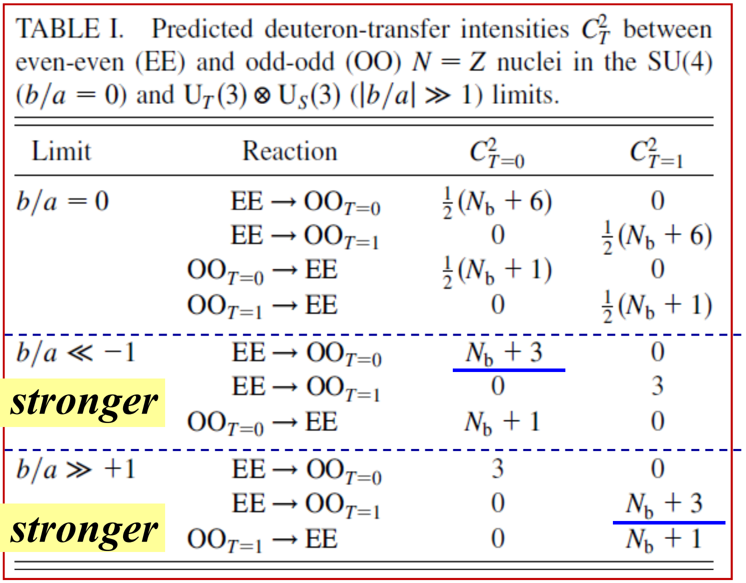


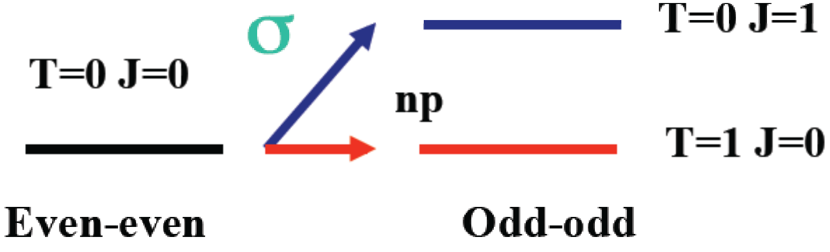
TABLE I. Predicted deuteron-transfer intensities C_T^2 between even-even (EE) and odd-odd (OO) $N = Z$ nuclei in the SU(4) ($b/a = 0$) and $U_T(3) \otimes U_S(3)$ ($|b/a| \gg 1$) limits.

Limit	Reaction	$C_{T=0}^2$	$C_{T=1}^2$
$b/a = 0$	$EE \to OO_{T=0}$	$\frac{1}{2}(N_b + 6)$	0
	$EE \to OO_{T=1}$	0	$\frac{1}{2}(N_b + 6)$
	$OO_{T=0} \to EE$	$\frac{1}{2}(N_b + 1)$	0
	$OO_{T=1} \to EE$	0	$\frac{1}{2}(N_b + 1)$
$b/a \ll -1$	$EE \to OO_{T=0}$	$\underline{N_b + 3}$	0
	$EE \to OO_{T=1}$	0	3
	$OO_{T=0} \to EE$	$N_b + 1$	0
$b/a \gg +1$	$EE \to OO_{T=0}$	3	0
	$EE \to OO_{T=1}$	0	$\underline{N_b + 3}$
	$OO_{T=1} \to EE$	0	$N_b + 1$

T=0 stronger

T=1 stronger

T=0 (T=1) pairing:
enhanced transfer probabilities
$0^+ \to 1^+$ ($0^+ \to 0^+$) levels



Reactions

(p, ^{3}He), (^{3}He,p)	ΔT=0,1
(d,α), (α,d)	ΔT=0
(α, ^{6}Li), (^{6}Li,α)	ΔT=0

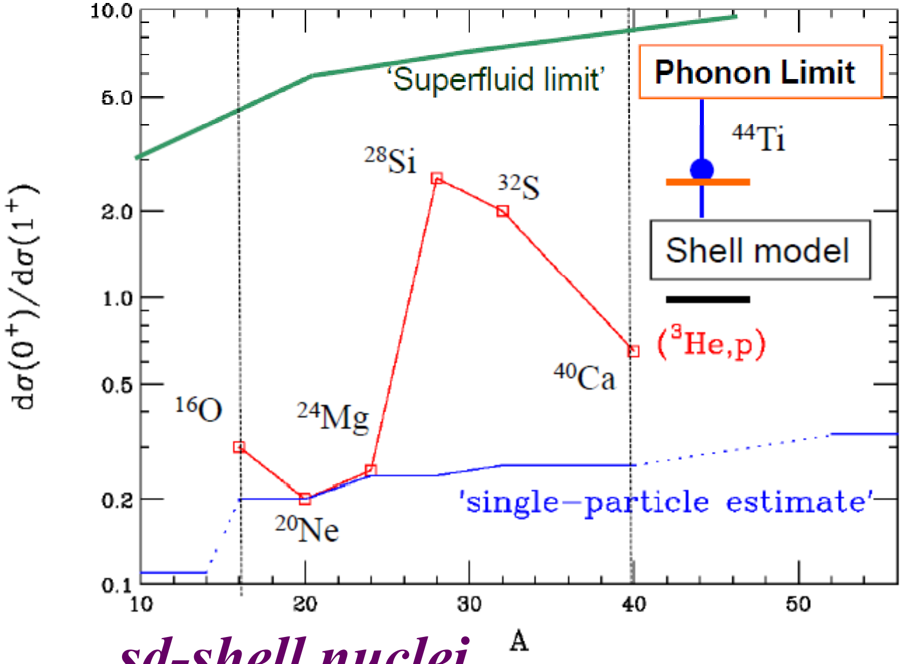
Measure the np transfer cross section to T=1 and T=0 states

Absolute σ(T=1) and σ(T=0) – character and strength of the correlations

σ(T=1) /σ(T=0) – interplay of T=1 and T=0 pairing modes

Framework of *np*-transfer for pairing

$\sigma(0^+)/\sigma(1^+)$: Interplay of T=0 & T=1 *np* pairing



sd-shell nuclei

Figure from A. Macchiavelli

Shiro Yoshida, NP 33, 685 (1962)

Superfluid limit ~ $(2\Delta_{T=1}/G)^2$

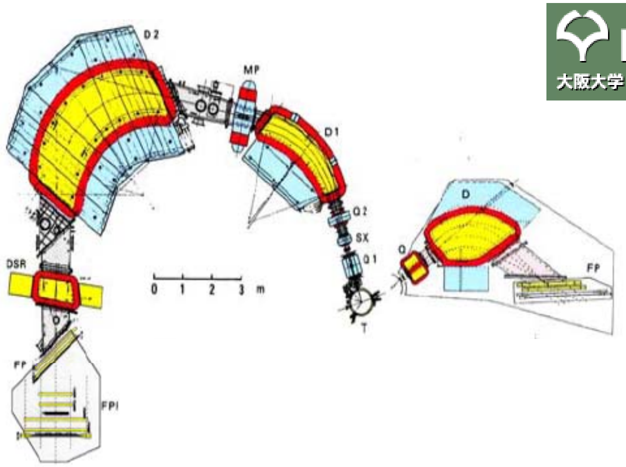
Single-particle estimate ~ (spin)x(^{3}He)x(LS -> jj)

Systematic measurements spanning ***sd*-shell** nuclei → Consistency

^{24}Mg(^{3}He,p), ^{32}S(^{3}He,p)

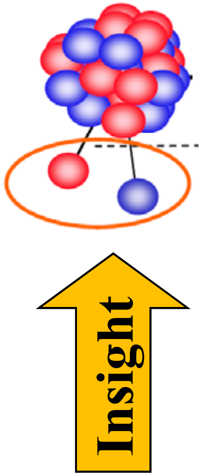
^{24}Mg(p,^{3}He), ^{28}Si(p,^{3}He) & ^{40}Ca(p,^{3}He)

RCNP 大阪大学 核物理研究センター



Framework & Baseline -- studies of np pairing in heavier N=Z nuclei (RI Beams)

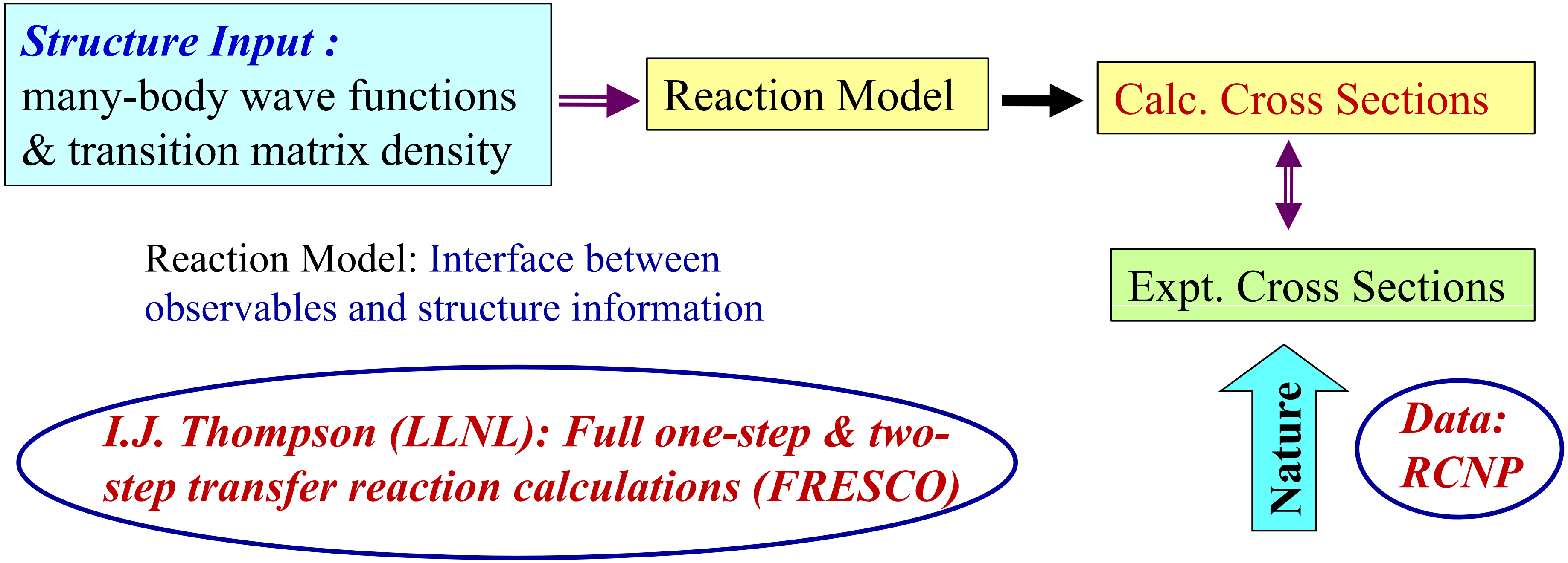
np-Transfer Reactions – Collaborative Efforts



New Structure of *np*-pairing:

- M. Horoi (CMU): transfer amplitudes from SM / pair operators
- Y. Sun (SJTU): matrix elements from spherical/ projected SM
- M. Matsuo (Niigata): formulating *np*-pairing using QRPA
- J. Meng (PKU): including T=0 *np*-pairing based on MF
- S.G. Zhou (CAS): extending SLAP to include *np*-pairing

Reaction Calculations + different structure models for *np*-pairing



Structure Input :
many-body wave functions
& transition matrix density

Reaction Model

Calc. Cross Sections

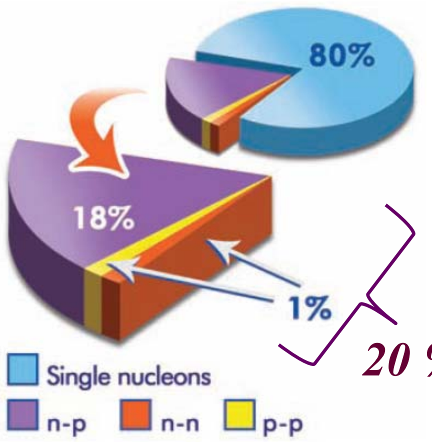
Expt. Cross Sections

Data: RCNP

Reaction Model: Interface between observables and structure information

I.J. Thompson (LLNL): Full one-step & two-step transfer reaction calculations (FRESCO)

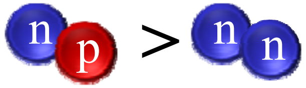
Neutron-Proton Knockout Reactions



80% nucleons - described in shell model

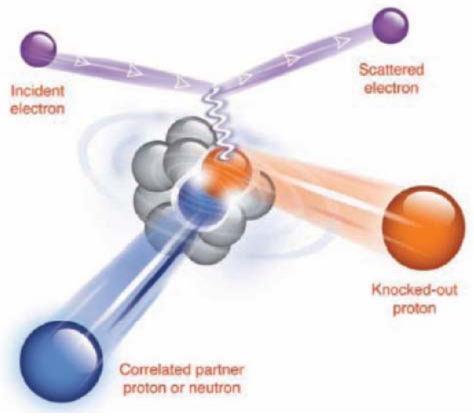
20 % correlated

18 times



Strong *NN* tensor force (short-range correlations)

^{12}C(*e,e'pN*) at 4.627 GeV



R. Subedi et al.,Science 320 (2008) 1476.

Reaction $^{12}C + ^{12}C \rightarrow X + anything$ (inclusive cross sections)

Sensitivity → Longer-Range of Correlations

For ^{12}C, 4*p* & 4*n* on $p_{3/2}$ shell
→No correlation: factor of 2.67 (pair counting)

Reaction Model → Underlying Physics

X	cross sections 250 MeV/nucleon
^{6}Li	26.35±2.1
^{7}Li	> 17.19±1.3
^{8}Li	> 1.33±0.34
^{7}Be	22.64±1.49
^{9}Be	10.44±0.85
^{10}Be	5.88±9.70
^{11}Be	0.36±0.26
^{8}B	< 3.21±0.59
^{10}B	47.50±2.42
^{11}B	65.61±2.55
^{12}B	< 0.49±0.67
^{10}C	5.33±0.81
^{11}C	55.97±4.06

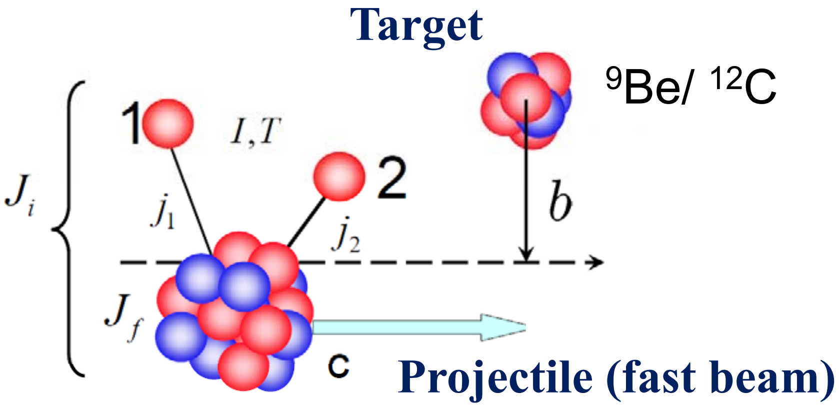
J.M. Kidd et al.,
PRC 37, 2613 (1988).

-2p

-np
factor of 8 !

-2n

Two-Nucleon Knockout Model



Theoretical Cross sections:

Reaction: Eikonal & Sudden approximation

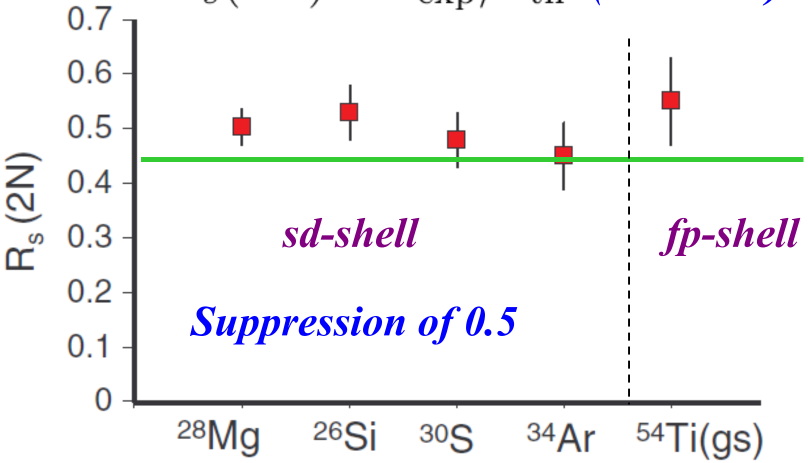
Structure: 2*N* Overlap from Shell Model

J. Tostevin, B.A. Brown, PRC **74**, 064604 (2006)

E.C. Simpson and J. Tostevin et al., PRL **102**, 132502 (2009)

2*n* or 2*p* knockout (T=1)

$R_s(2N) = \sigma_{\mathrm{exp}}/\sigma_{\mathrm{th}}$ ***(Inclusive)***



D. Bazin et al., Phys. Rev. Lett. 91, 012501 (2003)
K. Yoneda et al., Phys. Rev. C 74 , 021303(R) (2006)
A. Gade et al., Phys. Rev. C 74 , 021302(R) (2006)
P. Fallon et al., PRC 81, 041302(R) (2010)

Factor of 2 over-prediction → insufficient *2N* correlations in Shell Models in *sd-pf* shell

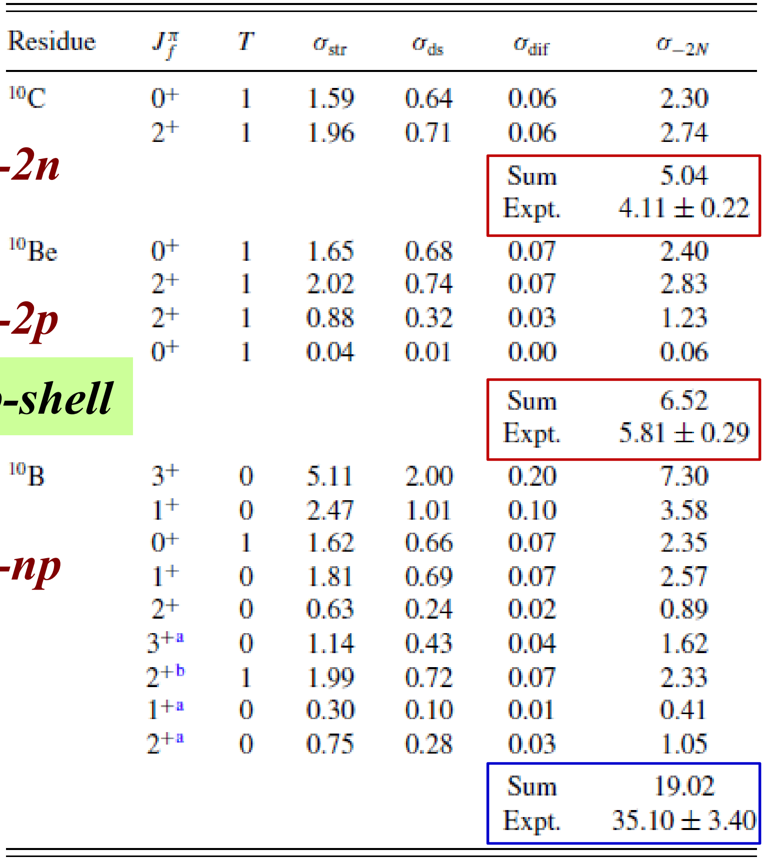
Framework to quantitatively assess descriptions of *2n & 2p* T=1 correlations

^{12}C – Interesting Physics found & hidden

Advanced Model *np* removal with T=0

First Calculations : np removal from ^{12}C

E.C. Simpson and J.A. Tostevin, PRC 83, 014605 (2011).



Residue	J_f^π	T	σ_{str}	σ_{ds}	σ_{dif}	σ_{-2N}
^{10}C	0^+	1	1.59	0.64	0.06	2.30
	2^+	1	1.96	0.71	0.06	2.74
					Sum	5.04
					Expt.	4.11 ± 0.22
^{10}Be	0^+	1	1.65	0.68	0.07	2.40
	2^+	1	2.02	0.74	0.07	2.83
	2^+	1	0.88	0.32	0.03	1.23
	0^+	1	0.04	0.01	0.00	0.06
					Sum	6.52
					Expt.	5.81 ± 0.29
^{10}B	3^+	0	5.11	2.00	0.20	7.30
	1^+	0	2.47	1.01	0.10	3.58
	0^+	1	1.62	0.66	0.07	2.35
	1^+	0	1.81	0.69	0.07	2.57
	2^+	0	0.63	0.24	0.02	0.89
	3^{+a}	0	1.14	0.43	0.04	1.62
	2^{+b}	1	1.99	0.72	0.07	2.33
	1^{+a}	0	0.30	0.10	0.01	0.41
	2^{+a}	0	0.75	0.28	0.03	1.05
					Sum	19.02
					Expt.	35.10 ± 3.40

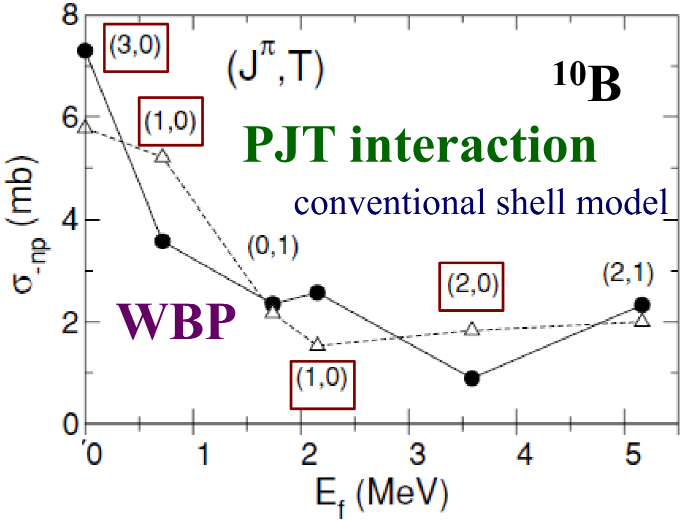
-2n

-2p

p-shell

-np

T=0 *np*-spatial correlations in the wave functions are insufficient



T=0 cross-sections – sensitive to effective interactions !

Data needed (exclusive measurement):
- guide Theoretical Developments
- gain Detailed knowledge

Wave Functions from different models:

-Variation Monte Carlo w/ 3-body force (ab initio) I. Brida (ANL)

- Tensor optimized shell model T. Myo (Osaka IT)

np knockout → T=0 *np* pairing ?

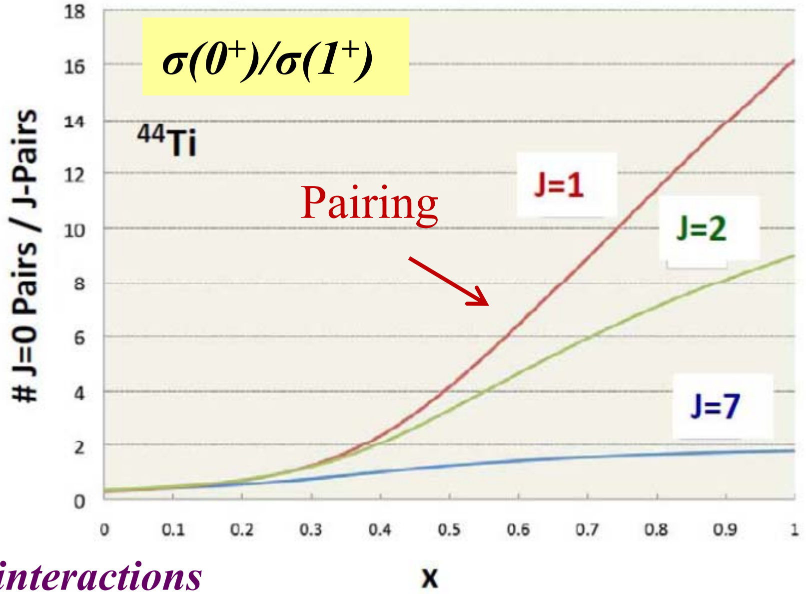
Searching since 60's: T=0 *np*-pairing exists ?

Knockout Cross sections (not spin selective)

→ **$\sigma(0^+)/\sigma(1^+)$ sensitive to T=0 pairing**

→ **<u>Systematic</u> (exclusive) measurements of *N*=*Z* nuclei: signal T=0 pairing (if any) – model independent !**

Calculations by A. Macchiavelli *(BNL)*



T=0 pairing interactions

Proposed Measurements

***np* Knockout: ^{12}C, ^{28}Si & ^{40}Ca on ^{12}C target**

(Not Spin-Selective)

Transfer: ^{12}C(p,^{3}He), <u>^{28}Si(p,^{3}He) & ^{40}Ca(p,^{3}He)</u>

(proton-beam)

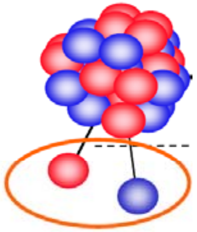
(Spin-Selective)

Quantify *np* pairing in knockout mechanism:

<u>Exclusive</u> Knockout Data
→compare to Transfer

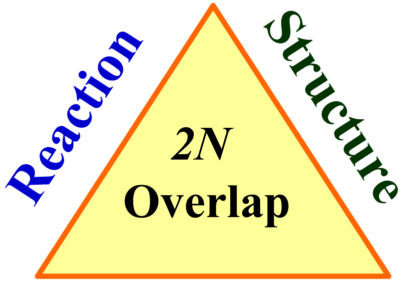
J. Tostevin (Surrey): knockout
I. Thompson (LLNL): transfer
M. Horoi (CMU): structure

→ framework – *np* pairing



Needs of Reaction Theory Support

Two-Nucleon Overlap



Data

Transfer Reactions:

○ No reliable models developed
○ Study reliability for high-energy transfer
○ Study reaction mechanism with light targets
○ How to incorporate structure information

^{9}Be or ^{12}C-induced *np*-Knockout Reactions:

✓ Surrey-Reaction Model (need data to verify)
○ Develop new Reaction model (T=0 & T=1 pair formulism)
○ Check energy dependence & Core-inert approximation

Proton-induced *(p,pd)* Knockout Reactions:

✓ Reaction Model (QMD, Y. Watanabe (Kyushu Univ.))
○ Different way to probe correlations
○ How to extract structure information

Future: Alpha Correlations using Direct Reactions
→ Need reaction model !

Outlook – Direct Reactions

E365: *np*-transfer Systematic Measurement spanning sd-shell nuclei

NSCL 09084: ^{34,46}Ar(p,d) at 70 A MeV

Future-proposed: Carbon-induced & proton-induced Knockout reactions of ^{14}O & ^{36}Ca at 250 A MeV

Future-proposed: First exclusive *np*-knockout of ^{12}C, ^{28}Si & ^{40}Ca

Future-proposed: ^{14}O beams on ^{12}C & CH_2 targets at 60 A MeV

Proton- & carbon-induced knockout (**diffractive & stripping** part separated)

Existing data (p,d) at 51 MeV @ GANIL → also learn relative influence

Idea: ^{14}O at 60 A MeV on CH_4 (Active Target) + *n*-detection → Core-breaking effects: ^{12}C → ^{4}He + ^{4}He + ^{3}He + n ***(support from reaction theorist !)***

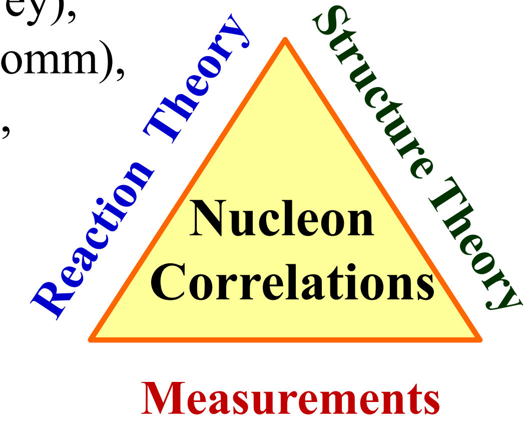
Intense Beams + Powerful Detectors + Computing → Dynamics of Nuclear Systems

Reliable reaction calculations:

- Need for experimental planning (setup, reaction energy) → most useful data
- Interpret data → mechanism behind nucleon correlations (underlying forces)

Acknowledgement

Plans of Correlation Studies using *1N* & *2N* Knockout and Transfer Reactions



Reaction: I. Thompson (LLNL), J. A. Tostevin, E.C. Simpson (Surrey), F. Flavigny (CEA Saclay), C. Bertulani, M. Karakoc (Texas A&M Comm), D.Y. Pang (Peking), Y. Aoki (RIKEN), T. Matsumoto (Hokkaido U.), K. Minomo, M. Yahiro, Y. Watanabe (Kyushu Univ.)

Structure: M. Matsuo (Niigata), Y. Utsuno (JAEA), I. Brida (ANL), T. Myo (Osaka IT), M. Horoi (CMU), J. Meng (Peking), Y. Sun (SJYU), S.G. Zhou (CAS)
(In progress: 2N-overlap ab initio & TOSM, MF sensitive to T=0)

Experiment: RIKEN group, RCNP group, A.O. Macchiavelli (BNL), A. Obertelli (CEA Saclay), R. Shane (MSU)