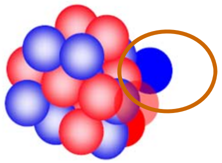
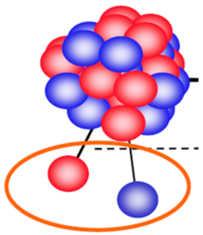
# Plans of Correlation Studies using *1N* & *2N* Knockout and Transfer Reactions

## Spectroscopic Overlaps



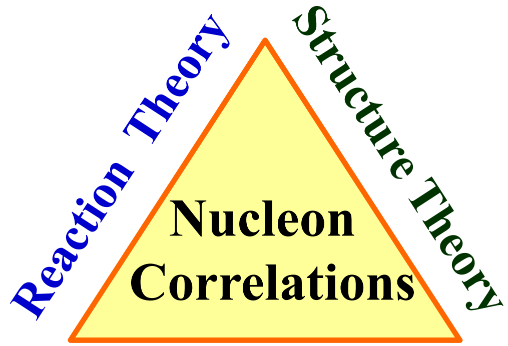
Spectroscopic Factor



Two-nucleon Overlap

Cross Section Measurements Coupled with Reaction and Structure theories

**Systematic Framework**




**Goal: Quantitative Knowledge of Nucleon Correlations**

**First Step:** Establish Reliable Framework

**Approach:** Appropriate Data Sets
(stable & exotic beams + normal & inverse kinematics)

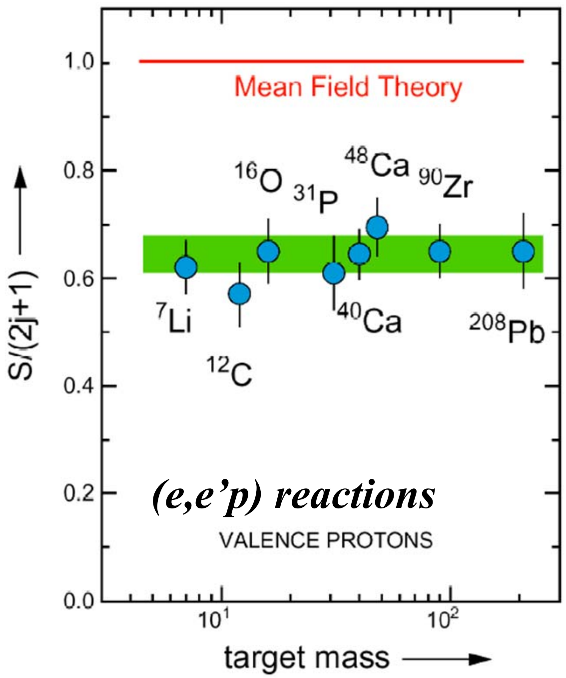
***Diff. Sensitivity → Collective (longer) / Tensor / Short-range Correlations***

# Spectroscopic Factor (SF)

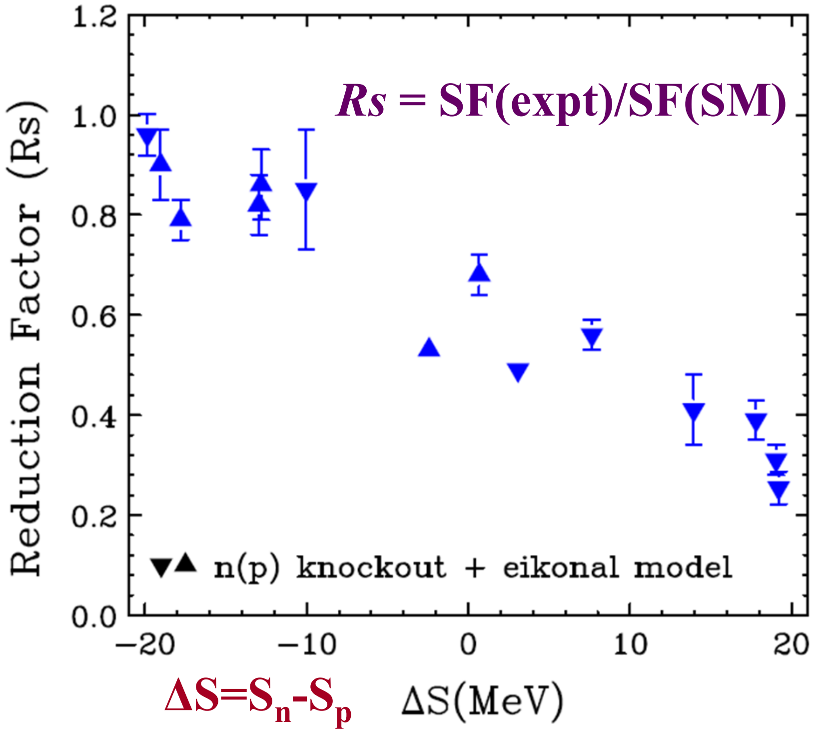
$$SF_{exp}/SF_{SM} < 1$$

**Some correlations missing in the interactions ?**

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




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



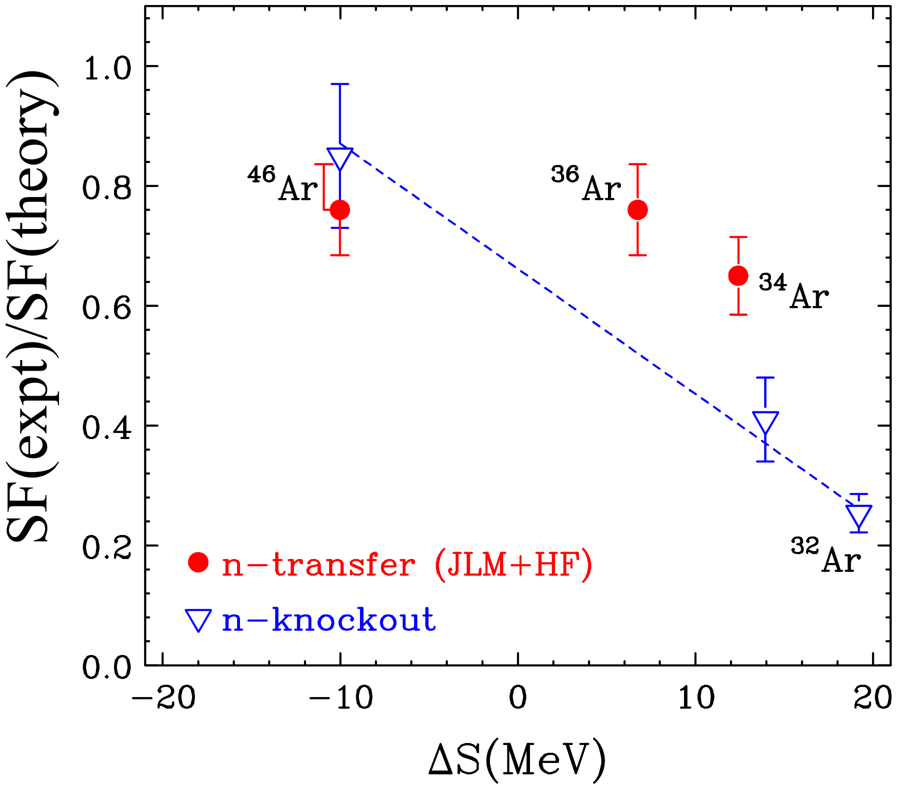

**(e,e'p) – Stable nuclei (near closed shell)**

- ***Constant ~30-40% of SF reduction***

**One-nucleon knockout -- away from stability**

- ***Rs*** **strongly depends on separation energy**

# 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 !***

***Inconsistency → Incomplete understanding in underlying reaction mechanism***

**Transfer Reaction**

✓ ***$^{34,46}$Ar(p,d) at 70 MeV/A***

***- same energy as knockout reactions***

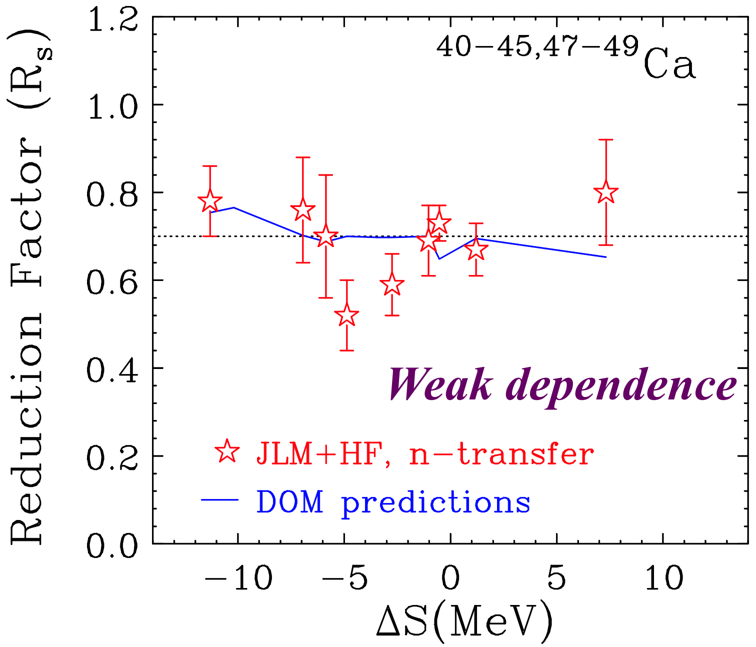
***- same SF from transfer at higher energy ?*** **(reliability and applicability of model)**

**Energy-Degraded Beam**

***→ compromise: beam quality & statistics – determines beam energy used***

**Knockout Reaction ?**

# Results from Other Calculations



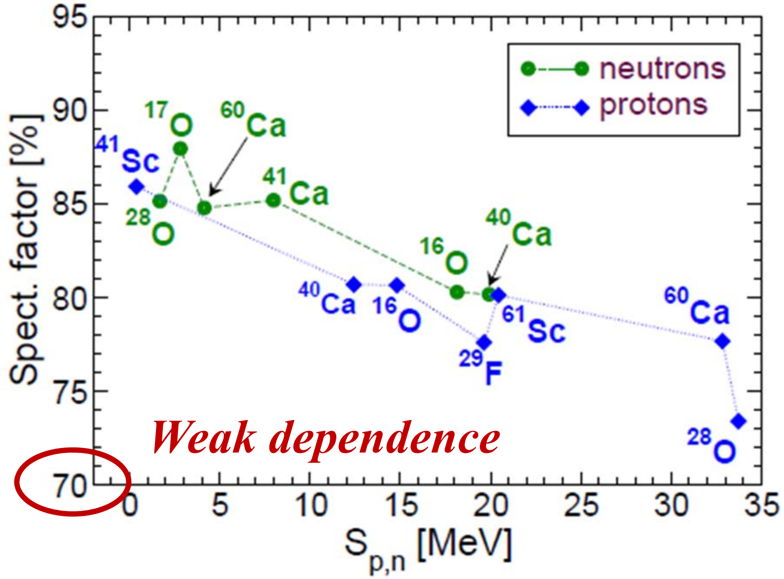

**Dispersive Optical Model (DOM)**

**(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**

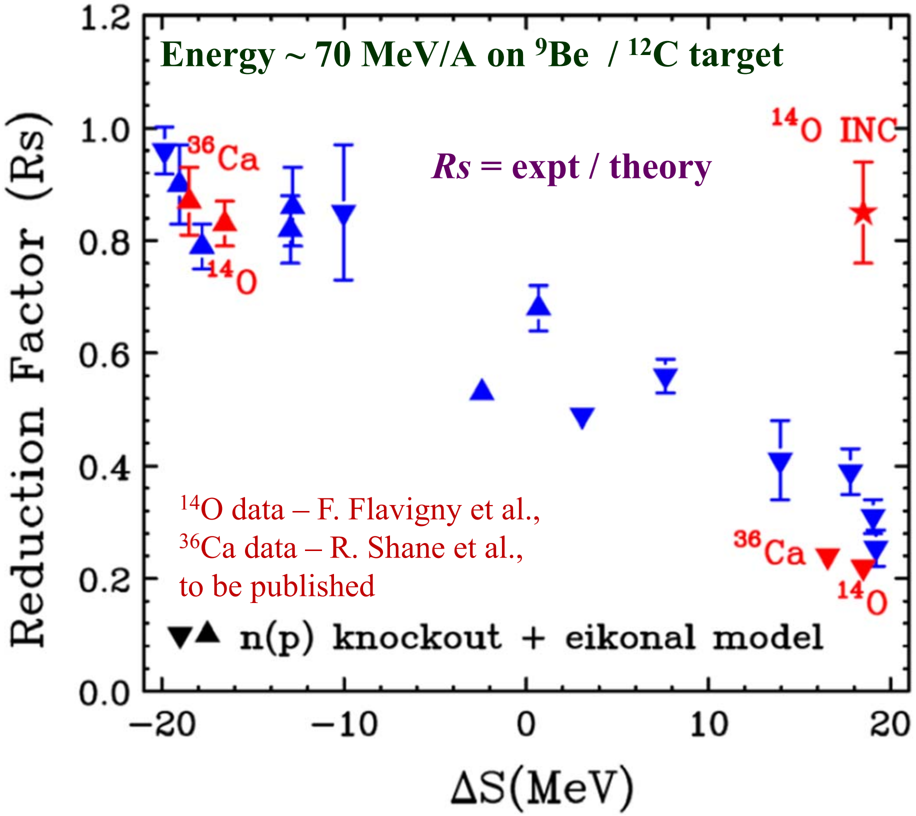
C. Barbieri & W. H. Dickhoff, arXiv:0901.1920v1




**Knockout reactions: Strong Dependence**

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

# Knockout Reaction Models




✓ 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

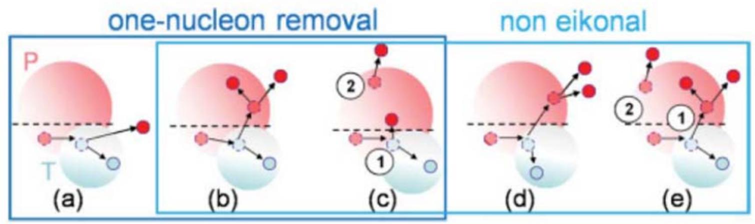
✓ Comparing physics from diff. reaction mechanisms

***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

**Intranuclear Cascade Model (*INC*)**

***(with nuclear-structure input)***

| Proj. | | $\ell j$ | $C^2S$ | $\sigma_{exp}$ (mb) | $\sigma_{casc}$ | $\sigma_{evap}$ (mb) | $\sigma$ | $\sigma_{eik}$ (mb) | $\delta$ |
|---|---|---|---|---|---|---|---|---|---|
| $^{14}$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)**

# Goals of Future-Proposed Measurements

Goal: Obtain a set of appropriate knockout reaction data

→ Verify the Reliability and Applicability of Reaction Models

→ Clarify the Isospin Dependence of Nucleon Correlations

Appropriate nuclei: **$^{14}$O, $^{36}$Ca ($Z$=8, 20)** - *sd*-shell, spherical nuclei

Reliable structure input → examine different reaction models

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**Step 1: Energy Dependence of Reaction Models**

*1n* & *1p* knockout at ~ 250 MeV/A for extreme-asymmetric nuclei

→ Compare to existing data at E ≤ 70 MeV/A

*No high-energy data for deeply-bound nucleon knockout*

***$\Delta S = |S_n - S_p|$: $^{14}O$ = 18.5 MeV ; $^{36}Ca$ = 16.6 MeV***

***Existing data: $^{14}O$ at 57 MeV/A ; $^{36}Ca$ = 70 MeV/A (~ 4 times lower)***

F. Flavigny et al., & R. Shane et al.,

Formalism of INC model – applied to nuclei with no bound excited states

***$^{14}O$, $^{13}N$, $^{13}O$, $^{36}Ca$, $^{35}Ca$, $^{35}K$ – only ground state bounded***

$^{12}$C( $^{14}$O, $^{13}$N), $^{12}$C( $^{14}$O, $^{13}$O), $^{12}$C($^{36}$Ca,$^{35}$Ca), $^{12}$C($^{36}$Ca,$^{35}$K) at 250 MeV/A

# Goals of Future-Proposed Measurements

RIKEN NISHINA CENTER

## Step 2: Core-excitation Effects & Constraints to Reaction Models

*INC calculations - $^{14}O + ^{9}Be$ @ 300 A MeV* C. Louchart et al.,

36 mb (1*p* to $^{13}$N), **18 mb** (1*n* to $^{13}$O),

**32 mb** (1*n* knockout +1*p* evaporation to $^{12}$N)

**52 mb** (1*n* knockout + 2*p* evaporation to $^{11}$C)

*Core-excitation effect - Significant*

$^{12}$C( $^{14}$O, $^{12}$N), $^{12}$C( $^{14}$O, $^{11}$C), $^{12}$C($^{36}$Ca, $^{33}$Ar) at 250 MeV/A

## Step 3: Compatibility of (*p,pN*) and $^{12}$C-induced knockout

**Quantitative comparison → insight into different mechanisms (target-effect)**

(p,pN) at ~250 MeV/A for exotic nuclei → valuable data

$^{1}$H( $^{14}$O, $^{13}$N), $^{1}$H( $^{14}$O, $^{13}$O), $^{1}$H( $^{36}$Ca,$^{35}$Ca), $^{1}$H( $^{36}$Ca,$^{35}$K),
$^{1}$H( $^{14}$O, $^{12}$N), $^{1}$H( $^{14}$O, $^{11}$C) & $^{1}$H( $^{36}$Ca, $^{33}$Ar) at 250 MeV/A

**14-reaction channels proposed:**

**proton- & $^{12}$C induced -1*n* & -1*p* knockout of $^{14}$O & $^{36}$Ca @ 250 AMeV**

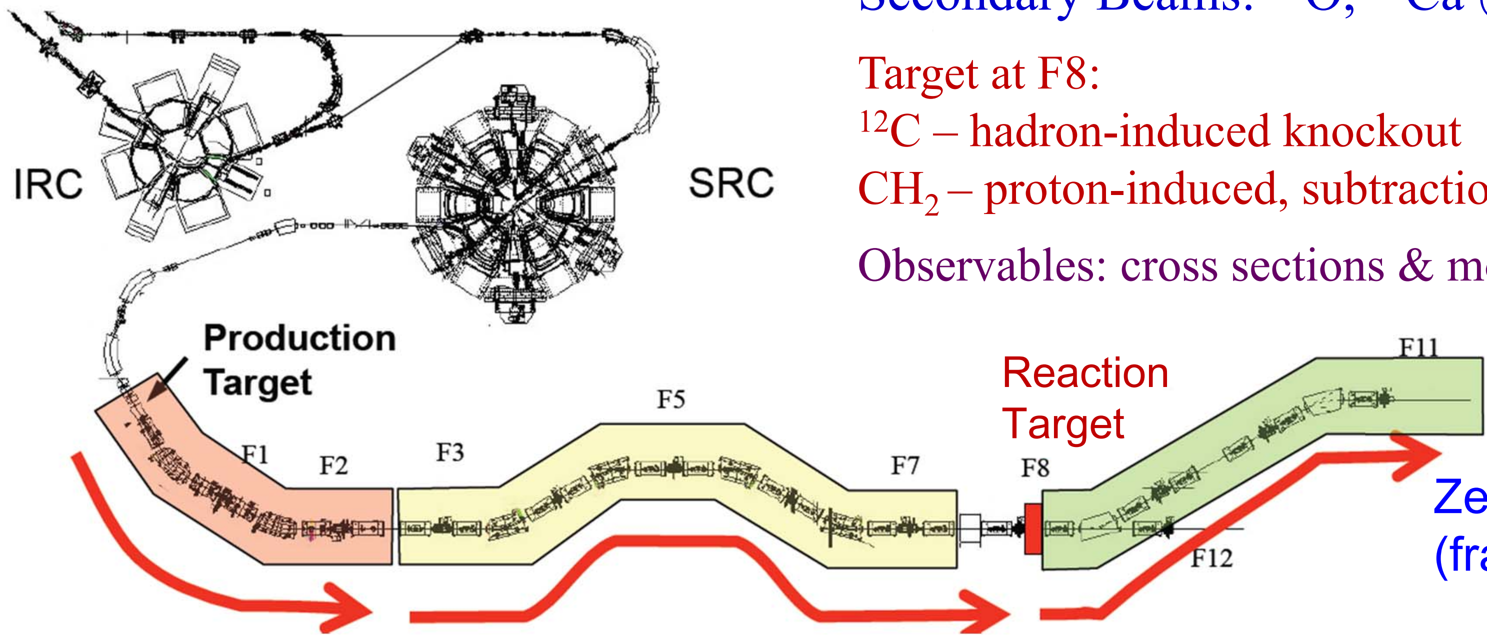
*Direct Comparison: $^{14}$O(d,$^{3}$He), $^{14}$O(d,t) @ GANIL* F. Flavigny et al.,

# Possible Experimental Setup

Secondary Beams: $^{14}$O, $^{36}$Ca @ 250 A MeV

Target at F8:
$^{12}$C – hadron-induced knockout
$CH_2$ – proton-induced, subtraction from $^{12}$C run

Observables: cross sections & momentum dist.




ZeroDegree
(fragment PID & $P_{//}$)

BigRIPS (Beam PID)

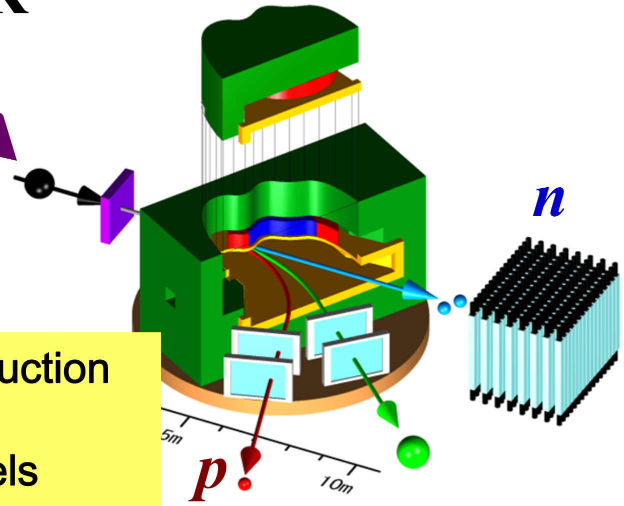
OR

- *1-N* removal: $^{13}$O, $^{13}$N, $^{35}$Ca, $^{35}$K
  – no bound excited states
  F. Flavigny et al., R. Shane et al., to be published
- Core-excitation Channel: $^{11}$C, $^{12}$N, $^{33}$Ar
  – Inclusive cross sections

No gamma-ray detectors needed

SAMURAI
(fragment PID & $P_{//}$
proton & neutron)

Kinematics Reconstruction
→ Core-excitation
(evaporation) channels



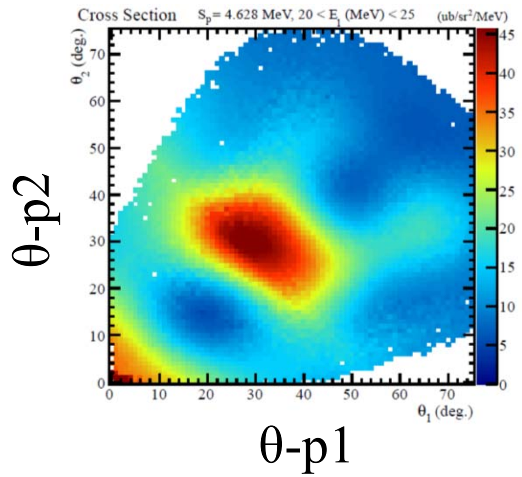
# Proton-Induced Knockout

## Consistency in SF extracted from different reaction models ?

- CDCC – reaction residues
- DWIA – scattered protons & knocked-out protons / neutrons
- New Model (Kyushu) – reaction residues (being developed)

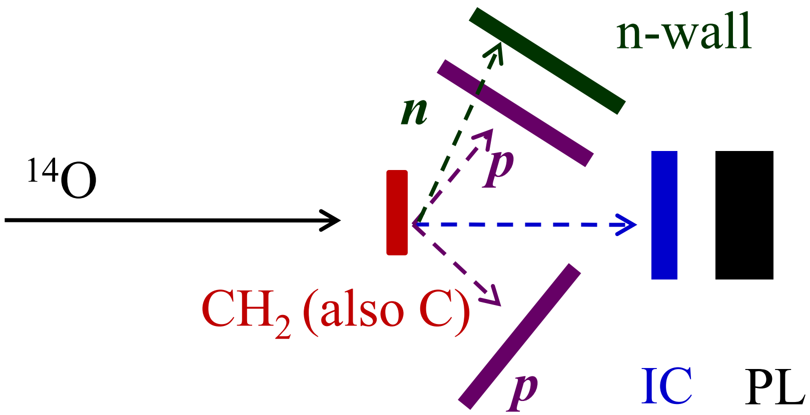
### Secondary Beams: $^{14}$O @ 60 A MeV

- Spherical → structure well known
- $^{13}$O & $^{13}$N → No bound excited states
- Light → reach of rigorous theoretical Calc. *(self-consistent Green's function, cluster method, tensor-optimized SM etc)*
- 60 A MeV → direct comparison to Be/C induced KO data




**$^{14}$O(p,2p) @ 60 AMeV**

DWIA Calc: S. Kawase (CNS)



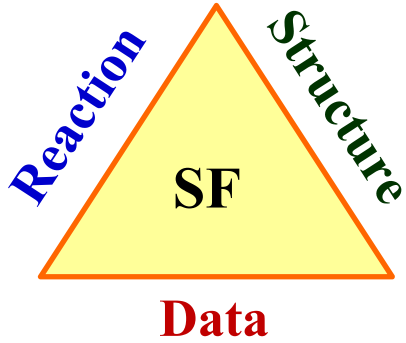

✓ **Energy & Angular distribution of *p & n***

→ disentangle diffractive & stripping parts
***(for both Knockout of weakly & deeply bound nucleon)***

→ detailed evaluation to model

# Needs of Reaction Theory Support

## Single-particle Overlap (SF)




**Transfer Reactions:**

✓ AWBA

- *Talks: F. Nunes, W. Catford, A. Wuosmaa, B. Tsang*

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

✓ Eikonal Reaction Model (J.A. Tostevin (Surrey))

- *Talk: A. Gade*

✓ 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:**

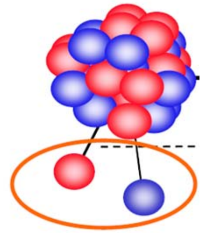
✓ CDCC calculations (T. Matsumoto (Hokkaido Univ.))

✓ DWIA calculations (S.Kawase (CNS) code:THREEDEE)

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

○ Future work

# Two-nucleon Overlap



## Two-like nucleon Transfer Reaction

### Similarity between pairing field and 2-body transfer operator

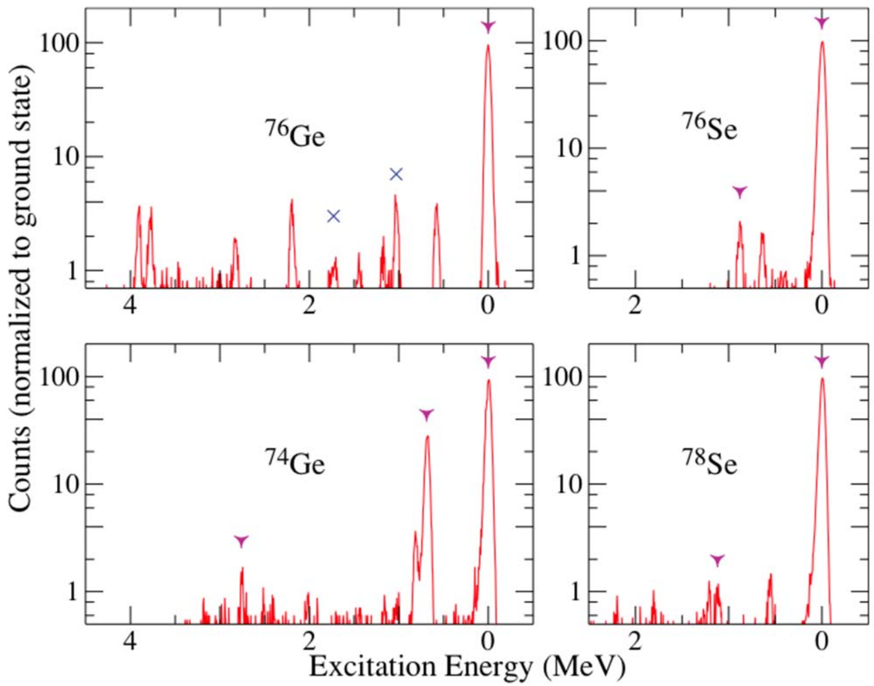
Two-nucleon transfer reactions like (t,p) or (p,t) → specific tool to probe T=1 pair correlations

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

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

***Spectra from (p,t) reactions***

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



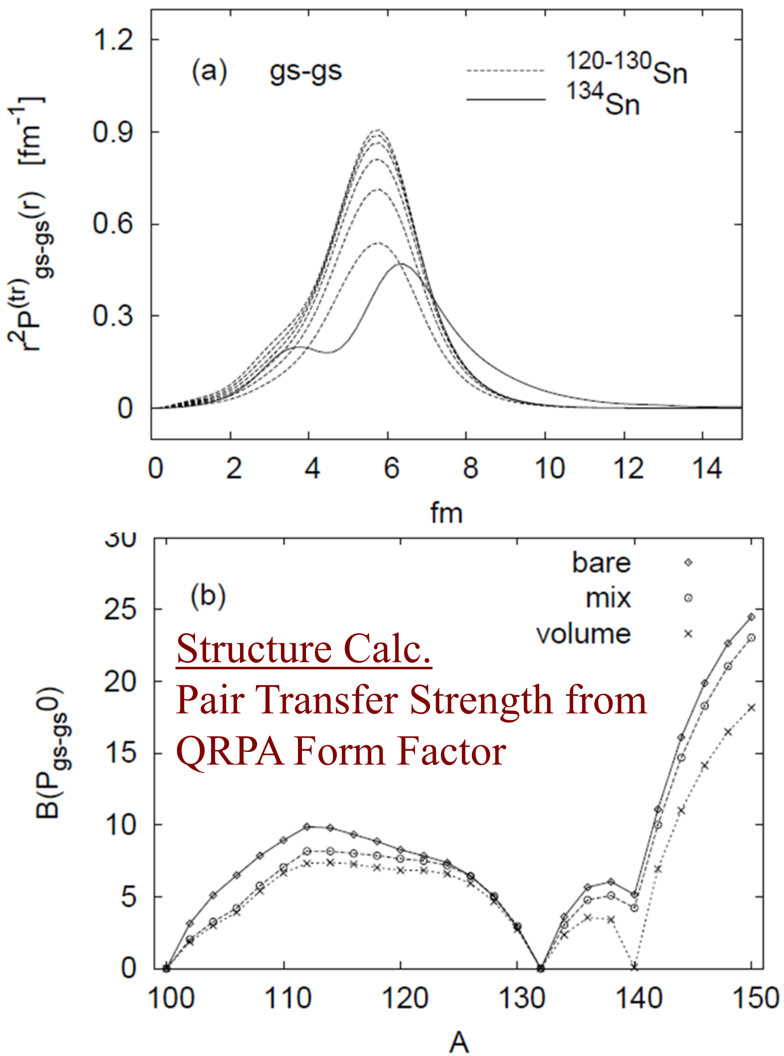

**$^{76}$Ge & $^{76,78}$Se(p,t) strength: predominately to the ground states → simple BCS paired states**

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

# *nn*-pairing in *Sn* Isotopes

Pair Transition density – Skyrme HFB + QRPA approach

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




***(p,t)* to resonance states → Width**

**Another useful observables ?**

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

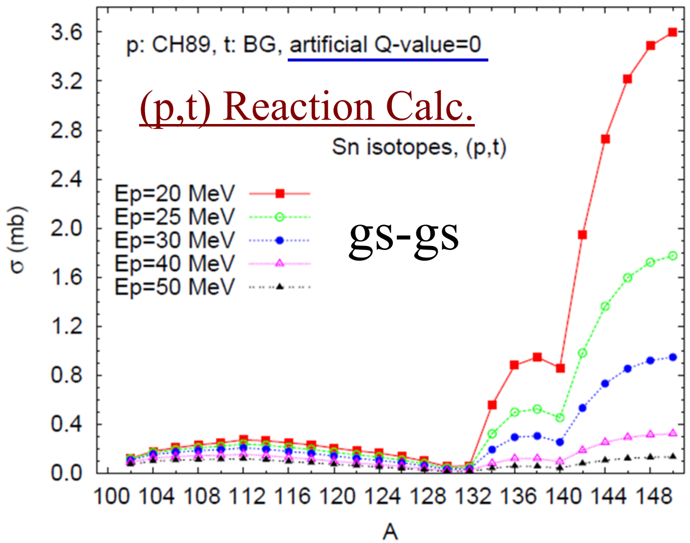
Insight → First Step: Systematic Reaction Calc.

One-step transfer +
QRPA Form Factor

Planned: Two-step Calculations

**TWOFNR, M. Igarashi et al., (Japan)**

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




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

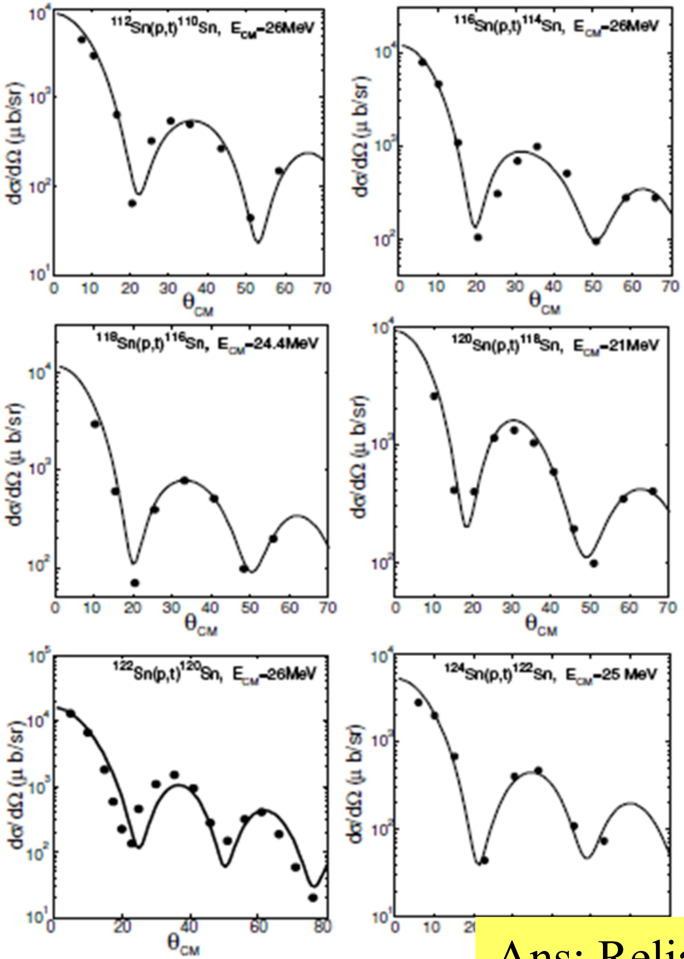
# Advanced 2*n* Transfer Calculations

***Calc. of absolute (p,t)*** **cross sections achieved:**

G. Potel et al., arXiv:1105.6250 in nucl-th

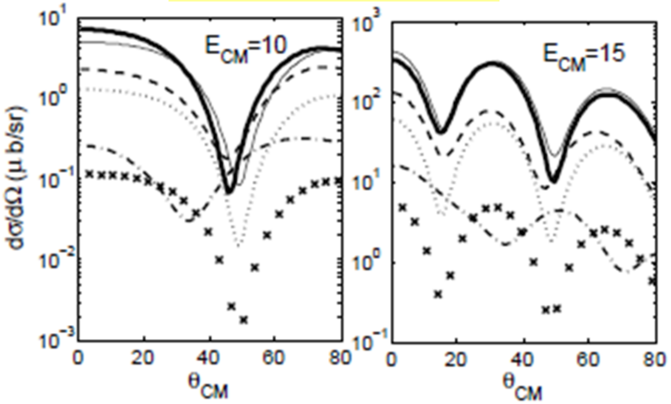
- Proper pairing interaction
- Multistep (successive, simultaneous)

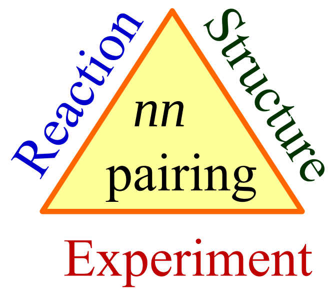
Framework: M. Igarashi et al.,




| | $\sigma(\mu b)$ | | | |
|---|---|---|---|---|
| | 5.11 MeV | 6.1 MeV | 10.07 MeV | 15.04 MeV |
| total | $1.29\times10^{-17}$ | $3.77\times10^{-8}$ | 39.02 | 750.2 |
| successive | $9.48\times10^{-20}$ | $1.14\times10^{-8}$ | 44.44 | 863.8 |
| simultaneous | $1.18\times10^{-18}$ | $8.07\times10^{-9}$ | 10.9 | 156.7 |
| non–orthogonal | $2.17\times10^{-17}$ | $7.17\times10^{-8}$ | 22.68 | 233.5 |
| non–orth.+sim. | $1.31\times10^{-17}$ | $3.34\times10^{-8}$ | 3.18 | 17.4 |
| pairing | $1.01\times10^{-19}$ | $6.86\times10^{-10}$ | 0.97 | 14.04 |

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




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

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

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

Ans: Reliable Reaction Calc. → expt. Planning → most useful data

# Neutron-Proton Pair Correlations

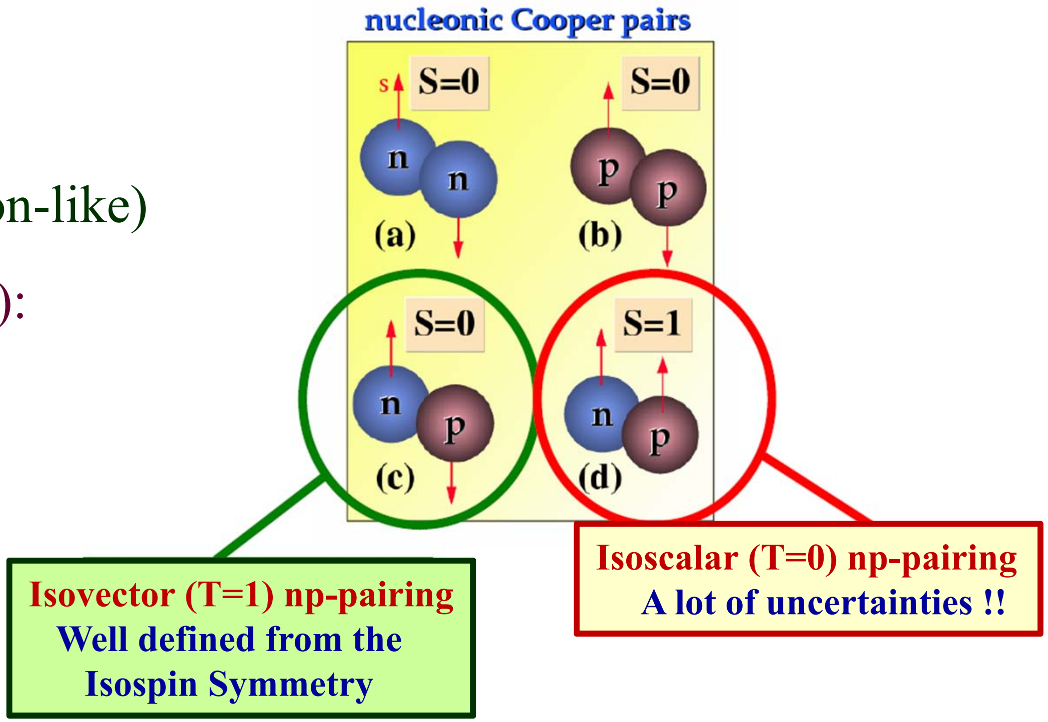
## In nuclei: 4 types of Pairs

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

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

Theories – MF, SM, IBM (since 60's):
Contradicting opinions & results !

**Spin-triplet pairing in large nuclei**
G. F. Bertsch and Y. Luo
Phys. Rev. C 81, 064320 (2010)




**Long-standing fundamental questions:**

- ○ **Nature of T=0 pair in nuclear medium ?**
- ○ **Mutual Strength & Interplay of T=0 and T=1 *np*, *nn*, *pp* pairs ?**
- ○ **Does T=0 pairing give rise to collective modes ?**

**<u>*N*=*Z* nuclei</u> - large spatial overlap between *n* & *p* in the same orbital**

# Previous Observables for *np*-pairing

***Extra Binding Energy of N=Z nuclei***
***"Wigner Energy"***

PHYSICAL REVIEW C, VOLUME 61, 041303(R)

### Is there *np* pairing in $N=Z$ nuclei?

A. O. Macchiavelli, P. Fallon, R. M. Clark, M. Cromaz, M. A. Deleplanque,
F. S. Stephens, C. E. Svensson, K. Vetter, and
*Nuclear Science Division, Lawrence Berkeley National Laboratory,*
(Received 15 April 1999; published 10 March

***T(T+1) – simple symmetry energy***

The binding energies of even-even and odd-odd $N=Z$ nuclei are compared. After correcting for the symmetry energy we find that the lowest $T=1$ state in odd-odd $N=Z$ nuclei is as bound as the ground state in the neighboring even-even nucleus, thus providing evidence for isovector *np* pairing. However, $T=0$ states in odd-odd $N=Z$ nuclei are several MeV less bound than the even-even ground states. We associate this difference with the $T=1$ pair gap and conclude from the analysis of binding energy differences and blocking arguments that there is no evidence for an isoscalar (deuteronlike) pair condensate in $N=Z$ nuclei.

Physics Letters B 393 (1997) 1–6

### Competition between $T = 0$ and $T = 1$ pairing in proton-rich nuclei

W. Satuła [a,b,c,d], R. Wyss [a]
[a] *The Royal Institute of Technology, Physics Department Frescati, Frescativägen 24, S-104 05 Stockholm, Sweden*
[b] *Joint Institute for Heavy Ion Research, Oak Ridge, TN 37831, USA*
[c] *Department of Physics, University of Tennessee, Knoxville, TN 37996, USA*
[d] *Institute of Theoretical Ph*
Received 26 Au

***Mean-field term $T^2$ as symmetry energy, $T$ as np pairing***

**Abstract**

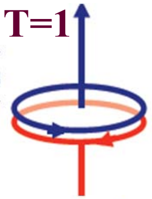
A cranked mean-field model with two-body $T = 1$ and $T = 0$ pairing interactions is presented. Approximate pro onto good particle-number is enforced via an extended Lipkin-Nogami scheme. Our calculations suggest the simul presence of both $T = 0$ and $T = 1$ pairing modes in $N = Z$ nuclei. The transitions between different pairing ph discussed as a function of neutron/proton excess, $T_z$, and rotational frequency, $\hbar\omega$. The additional binding energy d $T = 0$ *np*-pairing correlations, is suggested as a possible microscopic explanation of the Wigner energy term in nuclei.

***Proof of existence of T=0 pairing collectivity using B.E. depends on interpretations***

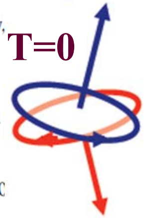
J. Dobaczewski, arXiv:nucl-th/0203063v1

***Rotational properties (high-spin aspect): moments of inertia, alignments***

T=1



T=0



VOLUME 87, NUMBER 13 PHYSICAL REVIEW LETTERS 24 S

### Alignment Delays in the $N = Z$ Nuclei $^{72}$Kr, $^{76}$Sr, and $^{80}$Zr

S. M. Fischer,[1] C. J. Lister,[2] D. P. Balamuth,[3] R. Bauer,[4] J. A. Becker,[4] L. A. Bernstein,[4] M. P. Carpent
N. Fotiades,[6] S. J. Freeman,[5] P. E. Garrett,[4] P. A. Hausladen,[3] R.
J. Schwartz,[2] D. Svelnys,[1] D. G. Sarantites,[8] D. Se

***Coriolis effect***

The ground state rotational bands of the $N = Z$ nuclei $^{72}$Kr, $^{76}$Sr, and $^{80}$Zr have been the angular momentum region where rotation alignment of particles is normally expected. the moments of inertia of these bands we have observed a consistent increase in the rotatic required to start pair breaking, when compared to neighboring nuclei. $^{72}$Kr shows the most marked effect. It has been widely suggested that these "delayed alignments" arise from *np*-pairing correlations. However, alignment frequencies are very sensitive to shape degrees of freedom and normal pairing, so the new experimental observations are still open to interpretation.

PHYSICAL REVIEW C **67**, 064318 (2003)

### Unravelling the band crossings in $^{68}$Se and $^{72}$Kr: The quest for $T=0$ pairing

S. M. Fischer
*Department of Physics, DePaul University, Chicago, Illinois 60614, USA*
*and Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

C. J. Lister
*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

D. P. Balamuth
*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
(Received 13 March 2003; published 27 June 2003)

been suggested to contain information on $T=0$ neutron- angular momentum states in the $N=Z$ populated through of these higher spin, and has resol extended to spin $J=26$ and a new band crossing into three bands, each of which has irregularities in its moment of ments indicate that the two high-spin bands have very different shapes. Similar, sharp established in both nuclei. A comparison of these data with recent measurements of $N=Z+2$ nuclei Se and $^{74}$Kr allowed the issue of "delayed alignments" to be addressed in detail. No clear-cut evidence for any delay was found.

***Change Experimental Observables from static properties → dynamic counterparts !***

# Neutron-Proton Transfer Reactions

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

## Deuteron Transfer in $N = Z$ Nuclei

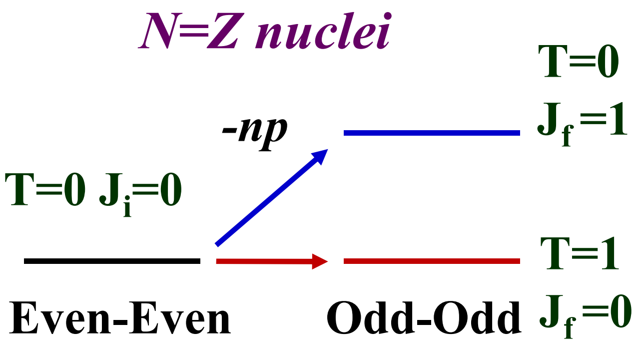
P. Van Isacker,[1] D. D. Warner,[2] and A. Frank[3]
[1]*Grand Accélérateur National d'Ions Lourds, B.P. 55027, F-14076 Caen Cedex 5, France*
[2]*CCLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[3]*Instituto de Ciencias Nucleares, UNAM, Apdo. Postal 70-543, 04510 México, D.F. 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 | $C^2_{T=0}$ | $C^2_{T=1}$ |
|---|---|---|---|
| $b/a = 0$ | $EE \rightarrow OO_{T=0}$ | $\frac{1}{2}(N_b + 6)$ | 0 |
| | $EE \rightarrow OO_{T=1}$ | 0 | $\frac{1}{2}(N_b + 6)$ |
| | $OO_{T=0} \rightarrow EE$ | $\frac{1}{2}(N_b + 1)$ | 0 |
| | $OO_{T=1} \rightarrow EE$ | 0 | $\frac{1}{2}(N_b + 1)$ |
| $b/a \ll -1$ | $EE \rightarrow OO_{T=0}$ | $N_b + 3$ | 0 |
| ***T=0 stronger*** | $EE \rightarrow OO_{T=1}$ | 0 | 3 |
| | $OO_{T=0} \rightarrow EE$ | $N_b + 1$ | 0 |
| $b/a \gg +1$ | $EE \rightarrow OO_{T=0}$ | 3 | 0 |
| | $EE \rightarrow OO_{T=1}$ | 0 | $N_b + 3$ |
| ***T=1 stronger*** | $OO_{T=1} \rightarrow EE$ | 0 | $N_b + 1$ |

**T=0 (T=1) pairing:**
***enhanced transfer probabilities***
***$0^+ \rightarrow 1^+$ ($0^+ \rightarrow 0^+$) 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

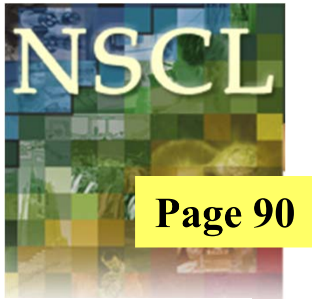
**σ(T=1) & σ(T=0) – pairing strength**
**σ(T=1) /σ(T=0) – interplay of T=1 and T=0 pairing modes**

# Plans - Transfer Reactions for *np*-pairing

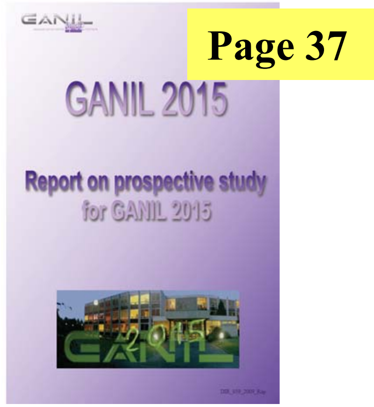
- ✓ **Intense *N*=*Z* Radioactive Beams**
- ✓ **Advanced detector systems (increased sensitivity + resolving power)**

→ **Renewed interest in *np*-pairing**

***np* transfer reaction → *np* pairing**




White paper
Isotope Science Facility
at Michigan State University
Upgrade of the NSCL rare isotope research capabilities




**Quantitative Physics of *np*-pairing ?**

**Methodology / framework established ?**

**Physics from light *N*=*Z* stable nuclei ?**

FUSTIPEN
French-U.S. Theory Institute for Physics with Exotic Nuclei

2011 FUSTIPEN Topical Meeting
on
« Neutron-proton pair correlations in N~Z nuclei »

February 3, 2011, GANIL, Caen, France

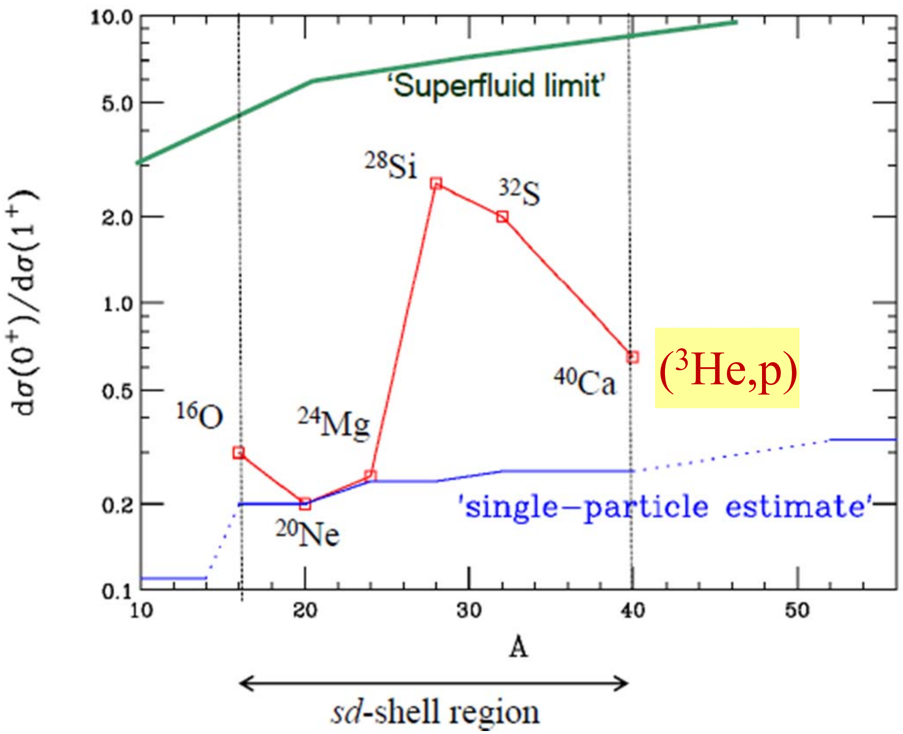
RIKEN NiSHiNA CENTER

**Probing Neutron-Proton Pair Correlations**
19-20 November 2010 | Nishina Memorial Building, RIKEN Wako-campus

Acknowledgement: George Bertsch & Augusto Macchiavelli for program advisory

# Systematics of T=0 & T=1 *np*-pairing in *sd*-shell

*N=Z nuclei in sd-shell*




**Ratio of cross section (T=1/ T=0)**
**- reducing systematic effects of absolute normalization**

from A. Macchiavelli *(BNL)*

**Shiro Yoshida, NP 33, 685 (1962)**

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

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

**Inconsistencies in the trends (*sd*-shell):**

- **Closed-shell nuclei $^{16}$O, $^{40}$Ca NOT follow single-particle estimate ?**
- **No intuitive understanding – $^{20}$Ne, $^{24}$Mg follow single-particle prediction ?**
- **Doubtful increase of > a factor of 10 from $^{24}$Mg to $^{28}$Si ?**

# Previous Measurements

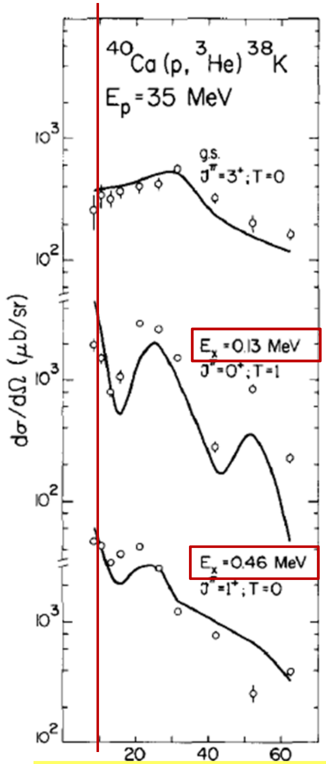
***np*-transfer:**
**$0^+ \rightarrow 0^+$ ($S$=0, $T$=1): $L$=0**
**$0^+ \rightarrow 1^+$ ($S$=1, $T$=0): $L$=0, 2**

- L=0 transfer dominant at forward angles (FA)

○ **FA → Meaningful & Clear Qualitative Comparisons**

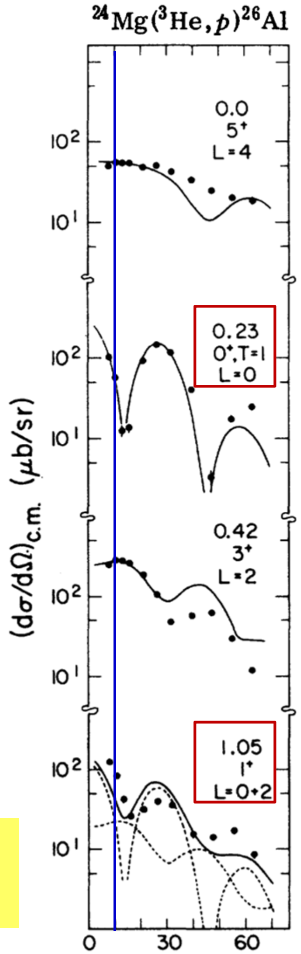
- Measurements in different experimental conditions, different groups, over 15 years !
- One measurement for each reaction → No consistency check

NPA407, 45(1983)



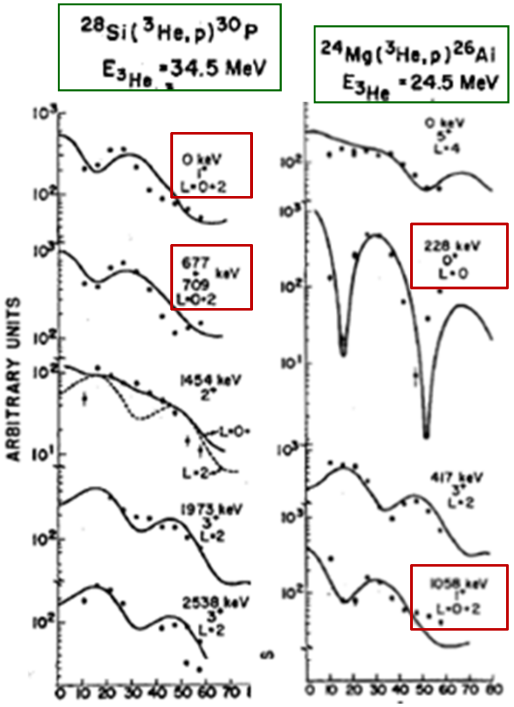

*No FA, insufficient data quality*

PRC23, 1305 (1981)




*No FA, not consistent with another measurement*

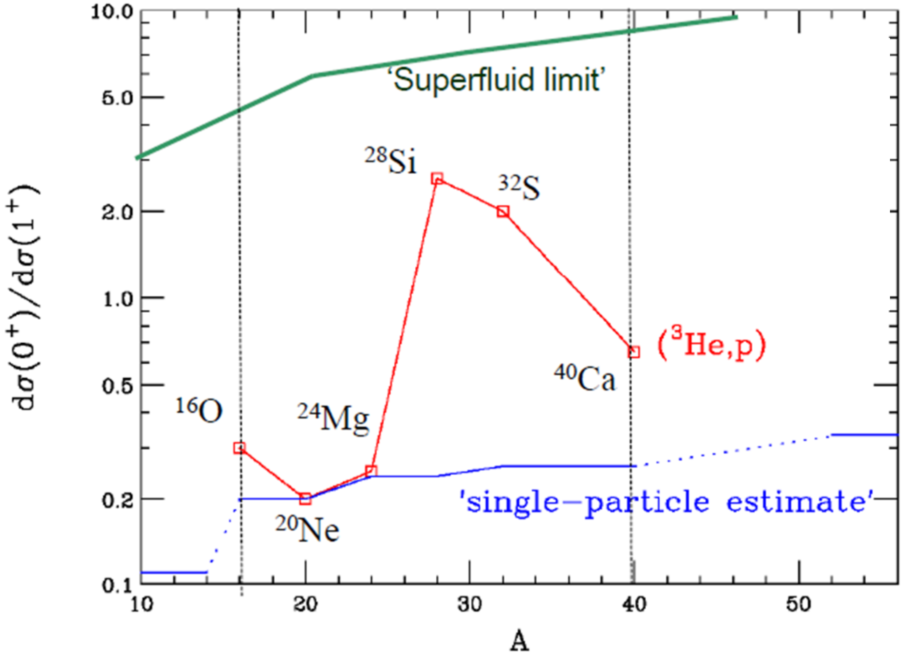
NPA265, 220 (1976)




*No FA, arbitrary unit*

**Need measurements dedicated to *np*-pairing studies !**

# **Goals:** Insight & quantitative knowledge of T=0 and T=1 *np*-pairing mechanism




**Joint analysis ($^{3}$He,p) & (p,$^{3}$He)**

→ Complete understanding – addition & removal transfer reactions for *np*-pairing

Five reactions proposed:

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

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

Normal Kinematics – Proton Beam !

✓ Systematic measurements **spanning** ***sd*-shell** nuclei under **SAME** condition

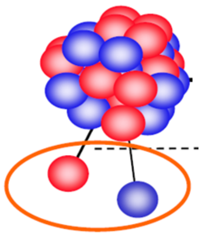
✓ **Consistent absolute** (dσ/dΩ) + **at 0º**
→ ***Reliable systematics***

– Interplay of T=0 and T=1 *np* pairing
– Individual T=0 & T=1 collectivity

***Systematic framework -- studies of np pairing in heavier N=Z nuclei (RI Beams)***

# *np*-Transfer Reactions – Collaborative Efforts

RCNP 大阪大学 核物理研究センター
RIKEN NiSHiNA CENTER



Insight

**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

Nature

*Data*

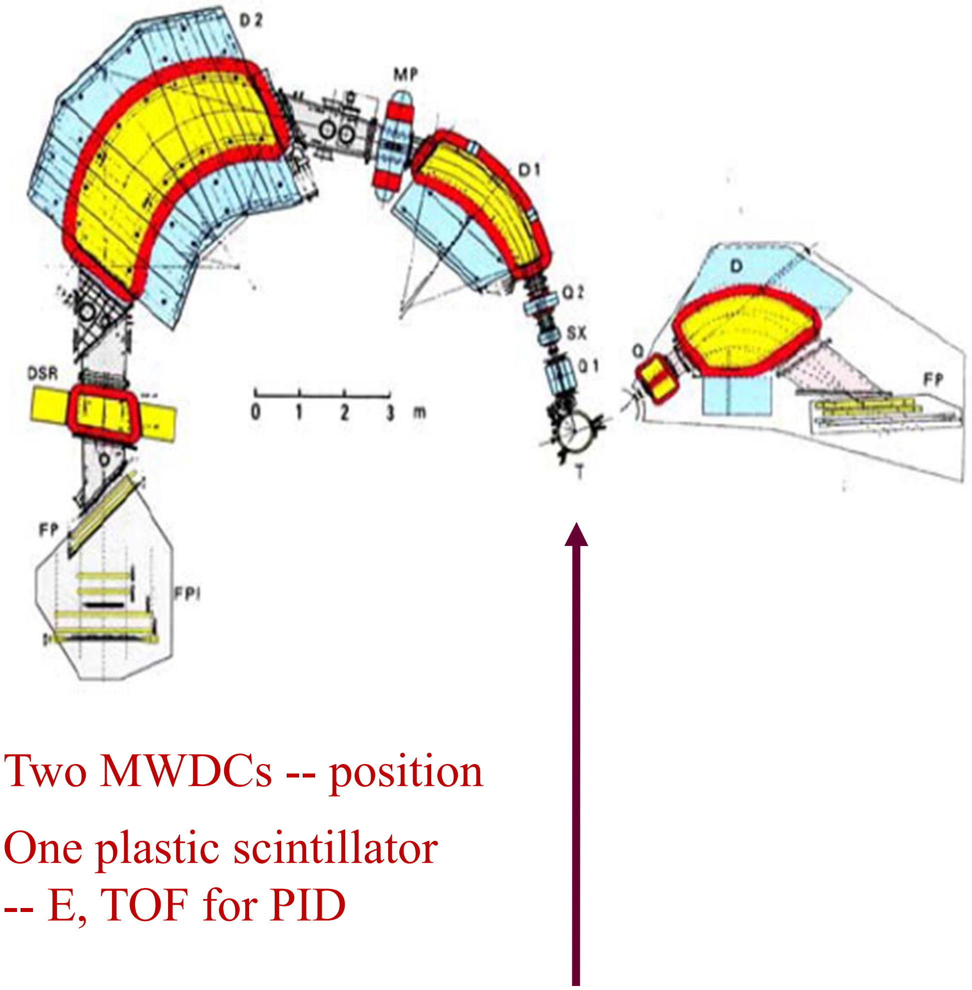
***I.J. Thompson (LLNL): Full one-step & two-step transfer reaction calculations (FRESCO)***

**How to incorporate different structure information into reaction model ?**

# Experimental Setup

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

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




Two MWDCs -- position

One plastic scintillator
-- E, TOF for PID

65 MeV proton / 25 MeV $^{3}$He
beams from injector AVF cyclotron

## RCNP: optimum conditions

***Grand Raiden (GR)*** spectrometer
→ Outgoing proton / $^{3}$He

GR + WS beam line (excellent resolution)
→ complex energy level of the odd-odd *N*=*Z* nuclei

Over-focused mode of GR
→ accurate reconstruction of scattering angles around 0°

***Large Acceptance spectrometer (LAS)***
→ monitoring target thickness for accurate normalization
→ elastic scattering channel at 60°

# E365 Collaborators for *np*-transfer experiment

**RIKEN**
J. Lee

**LLNL**
I. J. Thompson

**LBNL**
A.O. Macchiavelli, P. Fallon

**IPN Orsay**
D. Beaumel

**Science Faculty, Istanbul Univ.**
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**RCNP, Osaka U.**
N. Aoi, Y. Fujita,
K. Hatanaka, H. J. Ong,
T. Suzuki, A. Tamii,
Y. Yasuda, J. Zenihiro,

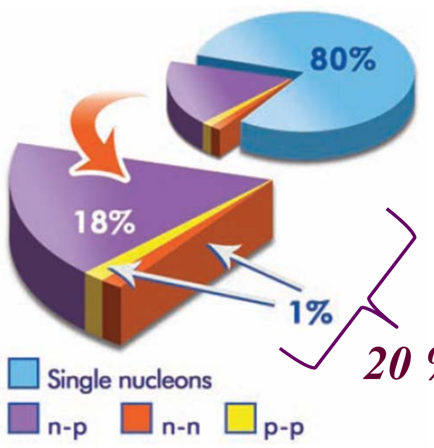
**Dep. Phys., Osaka Univ.**
H. Fujita

**CNS, Univ. of Tokyo**
H. Matsubara

**Dep. Of Physics, Kyoto Univ.**
T. Kawabata, N. Yokota

Acknowledgement: George Bertsch

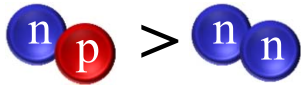
# Neutron-Proton Knockout Reactions




*80% nucleons - described in shell model*

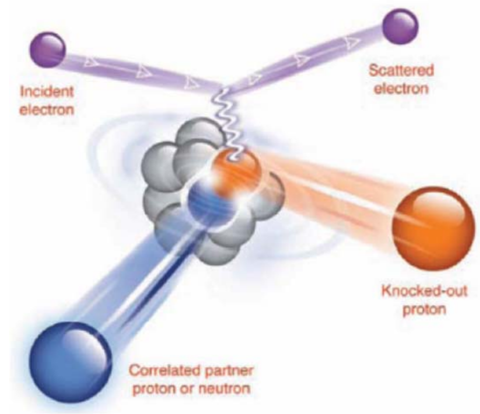
*20 % correlated*

**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**

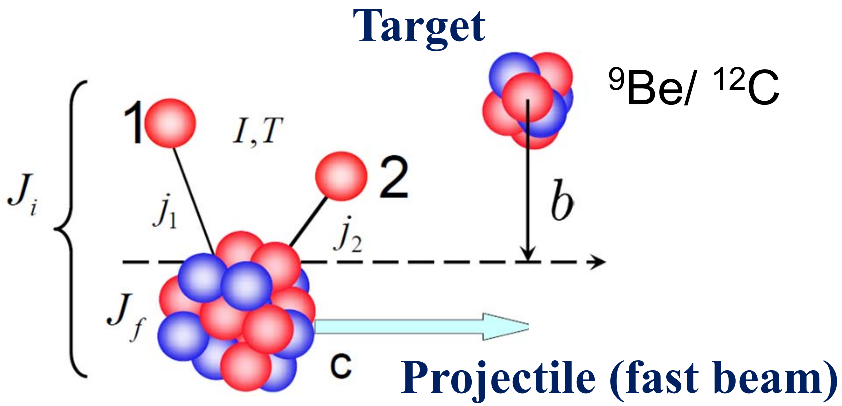
**For $^{12}$C, 4*p* & 4*n* on $p_{3/2}$ shell**
**→No correlation: factor of 2.67 (pair counting)**

**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 | *-2p* |
| $^{11}$Be | 0.36±0.26 | |
| $^{8}$B | < 3.21±0.59 | |
| $^{10}$B | 47.50±2.42 | *-np* *factor of 8 !* |
| $^{11}$B | 65.61±2.55 | |
| $^{12}$B | < 0.49±0.67 | |
| $^{10}$C | 5.33±0.81 | *-2n* |
| $^{11}$C | 55.97±4.06 | |

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

# Two-Nucleon Knockout Model




**Theoretical Cross sections:**

Reaction: Eikonal & Sudden approximation

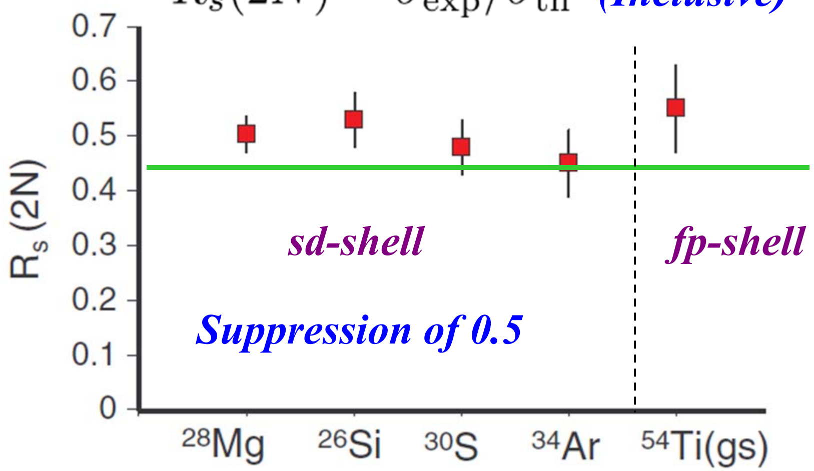
Structure: 2*N* Overlap from Shell Model

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)**

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

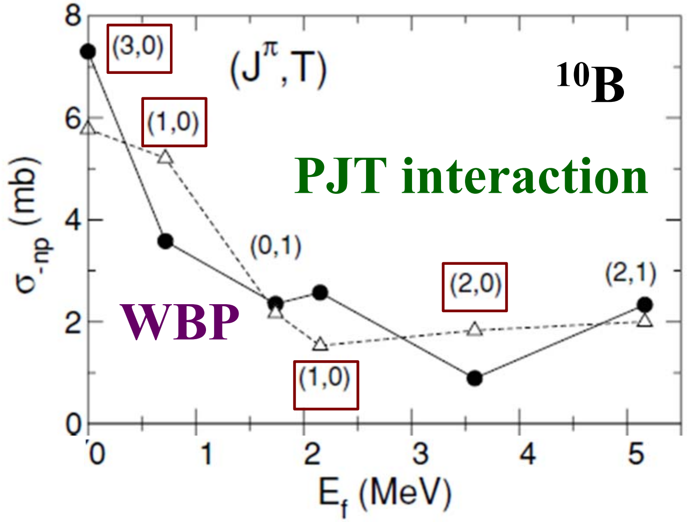
## Advanced Model *np* removal with T=0

*First Calculations : np removal from $^{12}C$*

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

-2n, -2p, *p-shell*, -np

| Residue | $J_f^\pi$ | $T$ | $\sigma_{str}$ | $\sigma_{ds}$ | $\sigma_{dif}$ | $\sigma_{-2N}$ |
|---|---|---|---|---|---|---|
| $^{10}C$ | $0^+$ | 1 | 1.59 | 0.64 | 0.06 | 2.30 |
| | $2^+$ | 1 | 1.96 | 0.71 | 0.06 | 2.74 |
| | | | | | Sum | 5.04 |
| | | | | | Expt. | $4.11 \pm 0.22$ |
| $^{10}Be$ | $0^+$ | 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. | $5.81 \pm 0.29$ |
| $^{10}B$ | $3^+$ | 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. | $35.10 \pm 3.40$ |




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

**Learned: Still Little, Not Detailed & Solid …**

**Structure T=0 interactions ? / Reaction Model ?**

**Theories reach Bottleneck …**

**Exclusive Data needed**
- **guide Theoretical Developments**
- **gain Detailed knowledge**

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

Only Inclusive data !

# Benchmark Framework + More Physics

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Action: **First exclusive-final-state measurement of *np*-knockout**
(cross sections & momentum distributions)

**1. Verify Reaction Model at spectroscopic level (individual states)**

**2. Direct observation on T = 0 channels → Confirm insufficient treatment of T=0 correlations**

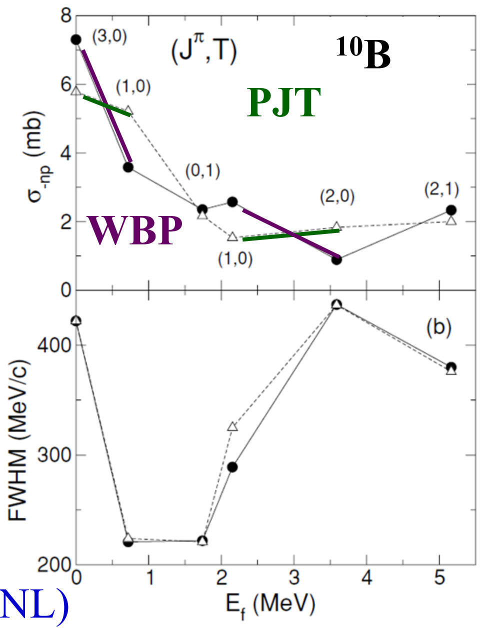
**3. Evaluate diff. interactions with expt. uncertainty ~10% (ratio:XS~factor of 2-4)**

**4. Width of $P_{//}$ - state-dependent → Further test structure input**

**5. Concrete reaction model → Assess *w.f.* from diff. structure models**

-Variation Monte Carlo w/ 3-body force I. Brida (ANL)
- Tensor optimized shell model  T. Myo (Osaka IT)

**6. Data → Useful to other reaction models**




| Residue | $J^\pi_f$ | $T$ | $\sigma_{-2N}$ |
|---|---|---|---|
| $^{10}$C | $0^+$ | 1 | 2.30 |
| | $2^+$ | 1 | 2.74 |
| | Sum | | 5.04 |
| | Expt. | | 4.11 ± 0.22 |
| $^{10}$Be | $0^+$ | 1 | 2.40 |
| | $2^+$ | 1 | 2.83 |
| | $2^+$ | 1 | 1.23 |
| | $0^+$ | 1 | 0.06 |
| | Sum | | 6.52 |
| | Expt. | | 5.81 ± 0.29 |
| $^{10}$B | $3^+$ | 0 | 7.30 |
| | $1^+$ | 0 | 3.58 |
| | $0^+$ | 1 | 2.35 |
| | $1^+$ | 0 | 2.57 |
| | $2^+$ | 0 | 0.89 |
| | $3^{+a}$ | 0 | 1.62 |
| | $2^{+b}$ | 1 | 2.33 |
| | $1^{+a}$ | 0 | 0.41 |
| | $2^{+a}$ | 0 | 1.05 |
| | Sum | | 19.02 |
| | Expt. | | 35.10 ± 3.40 |

**Both T=1 & 0**

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

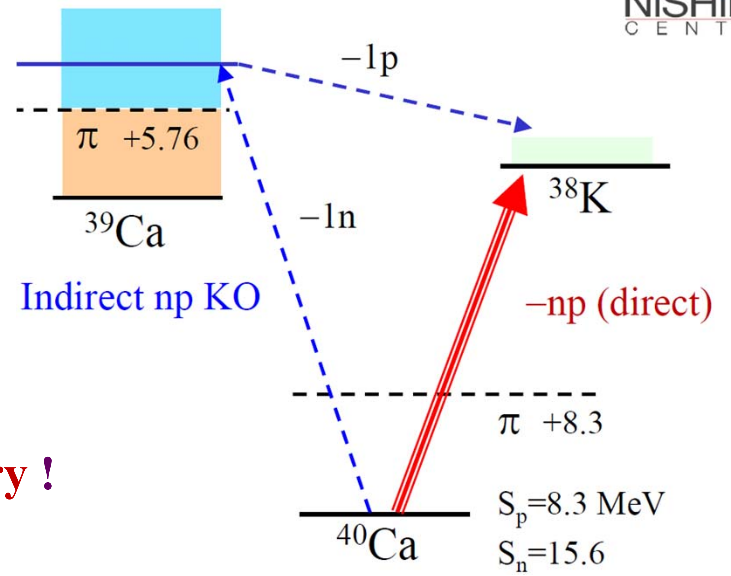
**First <u>exclusive</u> *np*-knockout : $^{12}$C**

# Experimental Challenges -- *N*=*Z* nuclei

### Large difference between $S_p$ & $S_n$

$$\sigma_{tot} = \sigma_{direct\text{-}np\ removal} + \sigma_{p\text{-}evap}$$

*Measured* *Direct (reaction model)* *Indirect*




**Direct KO data → Meaningful Comparison to Theory !**

One-step: -np knockout simultaneously

Two-step : -1n knockout followed by 1p evaporation

## Identification of Indirect *np*-knockout

**Detection of forward-angle protons**
(diagnostic: $P_{//}$ ($J=0^+$) & 1*N* removal)

- ✓ Kinematics considerations
- ✓ CDCC Calc. → Proton & residues distribution (Jeff Tostevin)
- ✓ Eikonal Calc. + MC Simulations

→ Width of $P_{//}$ from direct and indirect channels

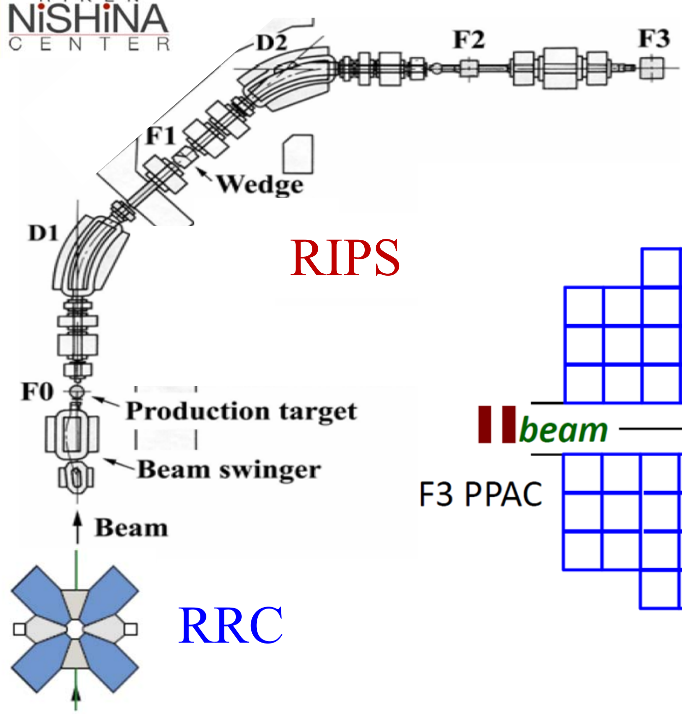
**$^{12}$C** ($S_n$=18.7, $S_p$=16.0 MeV)
**$^{28}$Si** ($S_n$=17.2, $S_p$=11.6 MeV)
**$^{40}$Ca** ($S_n$=15.6, $S_p$=8.3 MeV)

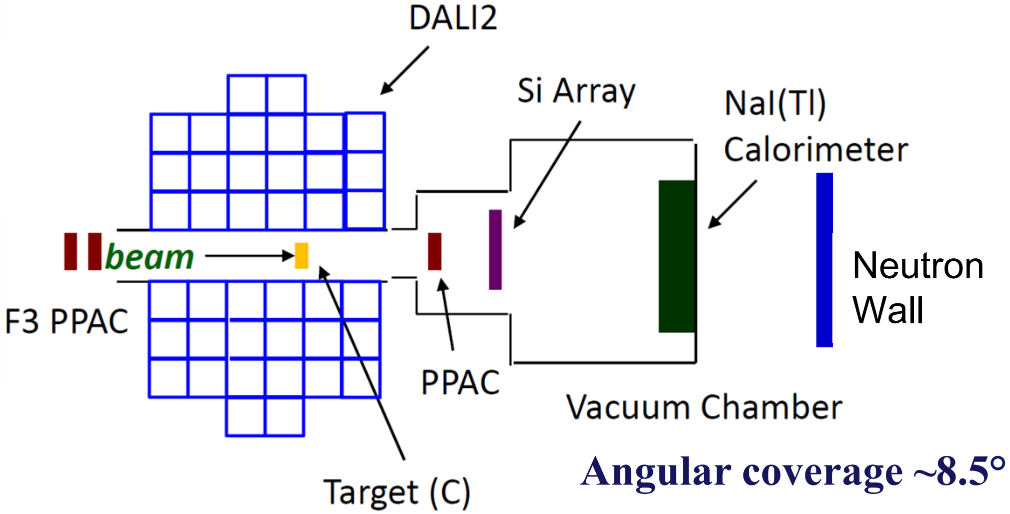
**Indirect knockout XS – Increasing !**

***Benchmark New Technique (np-KO $^{28}$Si, $^{40}$Ca)***
***→ Heavier N=Z – complex level-scheme***

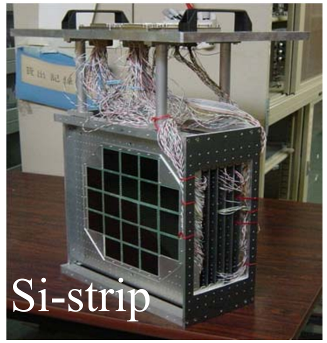
# Possible Experimental Setup

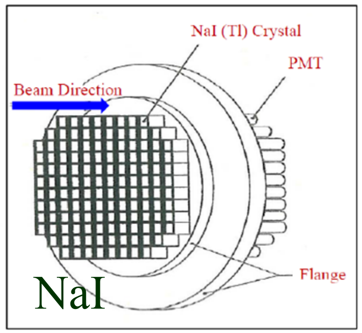
**Systematic Measurements :**
***np*-Knockout: $^{12}$C, $^{28}$Si and $^{40}$Ca**








Cross section (exclusive): γ-ray in coincidence with residues:

- DALI2 : γ detection → final states of residues & cross section
- Si + NaI(Tl) : TOF-ΔE, TOF-E → PID of residues

$P_{//}$ (exclusive):

- PPAC : Scattering angle of residues
- Si + NaI(Tl) : Total Energy

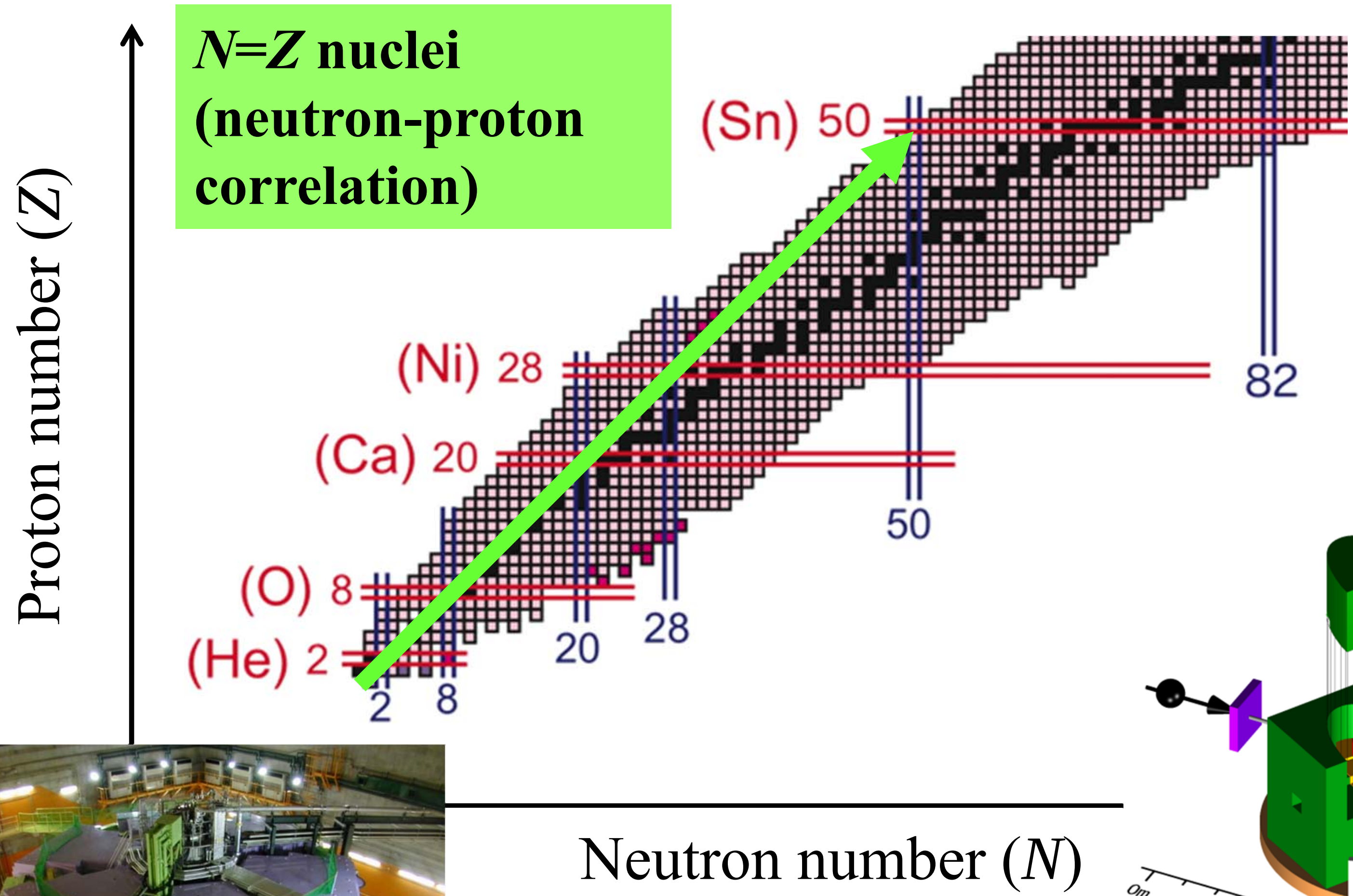
**10 % precision** on XS:
Systematic uncertainty form γ-ray detection

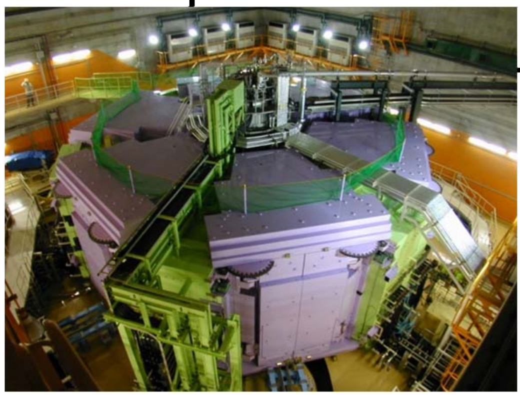
Identification of Indirect channel:

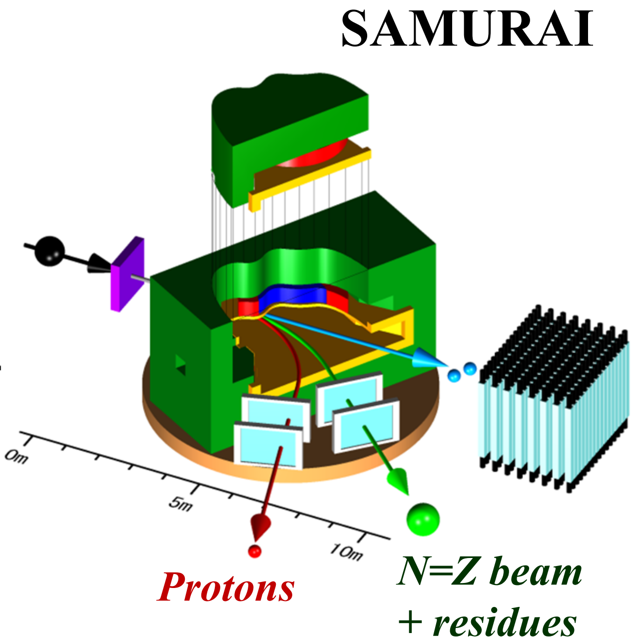
- Si + NaI(Tl): PID, Total Energy, scattering angle of proton

# Neutron-Proton Correlation in Exotic Nuclei

## Systematic Data*: np*-knockout of *N*=*Z* nuclei





# *np* knockout → T=0 *np* pairing ?

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

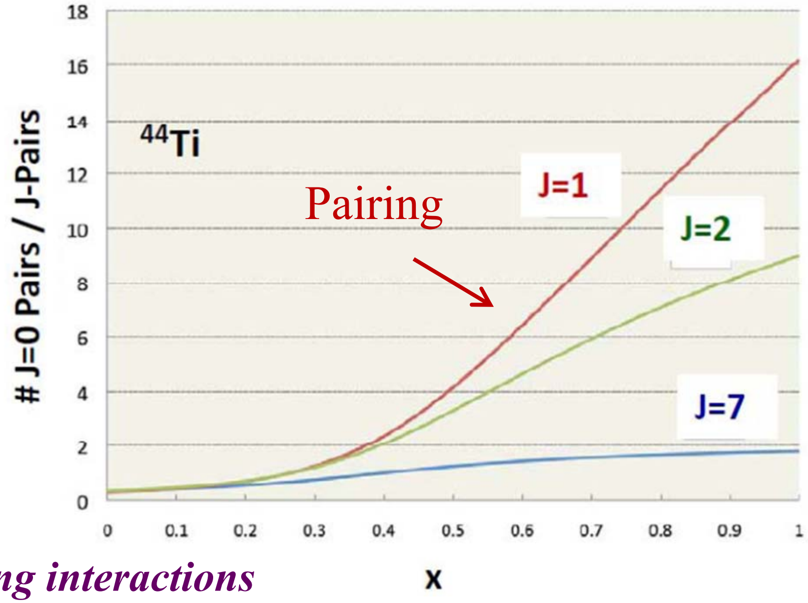
**Knockout Cross sections (not spin selective)**

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

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

$$H = x\, H_{(T=1,J=0)} + (1-x)\, H_{(T=0,J=1)}$$

**Calculations by A. Macchiavelli *(LBNL)***




***T=0 pairing interactions***

## Proposed Systematic Measurements

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

***(Not Spin-Selective)***

**Transfer: $^{12}$C(p,$^3$He), $^{28}$Si(p,$^3$He) & $^{40}$Ca(p,$^3$He)** (RCNP)

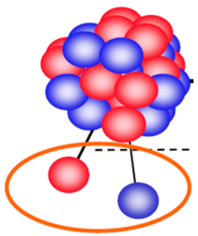
(proton-beam)

***(Spin-Selective)***

**Quantify *np* pairing in knockout mechanism:**

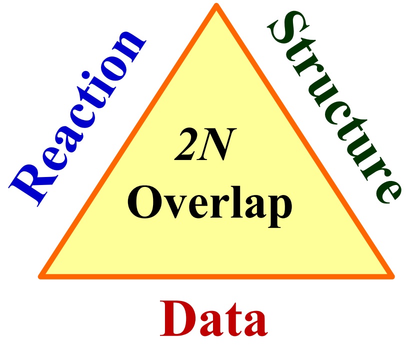
Exclusive Knockout Data
→compare to Transfer

**→ framework – *np* pairing**



# Needs of Reaction Theory Support

## Two-Nucleon Overlap




**Transfer Reactions:**

- ✓ Reliable models (I. J. Thompson (LLNL))
- ○ 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:**

- ✓ Eikonal Reaction Model (J.A. Tostevin (Surrey)) → Need data to verify !
- ○ Other Reaction models (T=0 & T=1 pair formalism)
- ○ Check energy dependence & core-inert approximation

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

- ○ Reaction Model (QMD approach by Y. Watanabe (Kyushu Univ.))
- ○ How to extract structure information

# Outlook – Measurements

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

Physics: Fundamental Nature & Interplay between T=0 & T=1 *np*-pairing

NEW Probe : Dynamical Implication of *np*-pairing

- ✓ Benchmark of np-pairing research using transfer reactions
- ✓ Baseline for systematic studies of np-pairing in heavier nuclei

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

Physics: SFs from transfer reactions & reaction mechanism at high energy

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

Physics: Clarify Isospin Dependence of Nucleon Correlations

A set of appropriate knockout reaction data

→ Verifying the Reliability and Applicability of Reaction Models

- ✓ Energy dependence of models
- ✓ Core-excitation effects
- ✓ Compatibility of different knockout mechanisms ($^{12}$C & proton)

# Outlook – Measurements

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

Physics: Neutron-Proton Correlations & Nature of T=0 pairs

NEW Probe : Dynamical Implication of *np*-correlations

✓ Benchmark: Reaction Model & Experimental Technique & Physics

✓ Foundation: Systematic studies of np correlations for exotic N=Z nuclei

Idea: proton-induced knockout $^{14}O$ at 60 A MeV

Physics: Consistent SF from different reaction models for same mechanism

Proton- & carbon-induced Knockout

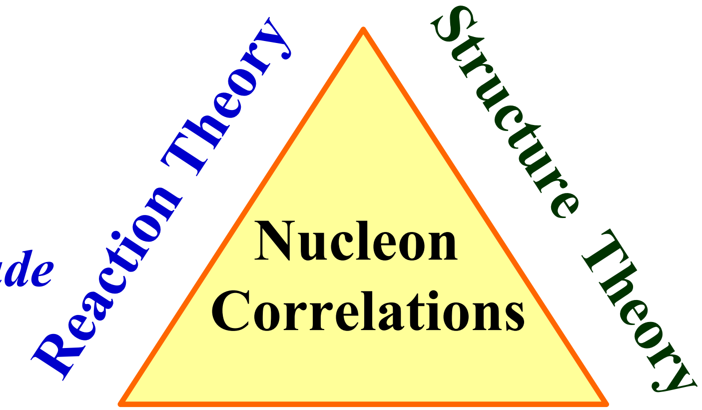
✓ Disentangle diffractive & stripping parts

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

✓ Evaluate models – different reaction mechanisms & energies

**This workshop will bring together experimenters and theorists to discuss the needs from each side and offer guidance for future research efforts.**

- *1-step & 2-step Transfer reactions*
- *Eikonal Model*
- *Intra-nuclear cascade*
- *CDCC*
- *DWIA*




- *Conventional SM*
- *Monte Carlo SM*
- *Tensor-optimized SM*
- *VMC / GFMC*
- *Mean-Field*

**Cross Section Measurements**

- *1N & 2N Transfer reactions*
- *Knockout reaction using Be / C target*
- *Knockout reaction using proton target*
- *Quasi-free scattering*

**To Theorists: Need Data to Benchmark the Models ?**

**Any "Direct" or "Clear-Cut" Observables ?**

# 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.), S. Kawase (CNS)

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

**Experiment:** RIKEN group, RCNP group, A.O. Macchiavelli, P. Fallon (LBNL), A. Obertelli (CEA Saclay), R. Shane, B. Tsang (MSU), D. Beaumel (Orsay)