Recent Experiments on Nucleon Correlation Studies using Knockout and Transfer Reactions

Jenny Lee

Radioactive Isotope Physics Laboratory

RIKEN Nishina Center for Accelerator-Based Science, Japan

Department of Physics, The University of Hong Kong

PKU-CUSTIPEN

Aug 10-14, 2014

Hong Kong

The University of Hong Kong

Nuclear Physics Group at The University of Hong Kong

HKU Group Members:
Zhengyu Xu (Postdoc)
Jiajian Liu (PhD student)
Taras Lokotko (PhD student)

- **Direct Reactions for Nucleon Correlations**
- **In-beam gamma Spectroscopy for Shell Evolutions**
  - 60 NaI Detectors → DALI2 Upgrade @ RIKEN
- **Beta-decay Spectroscopy for Shell Evolutions**

Upcoming Experiments

I) Asymmetry Dependence of Nucleon Correlations

Transfer reactions of $^{34,46}Ar$ at 70 MeV/u

National Superconducting Cyclotrons Laboratory, Michigan State University, United States (Dec 2014)

II) Alpha-cluster and Multi-neutrons in ^{14}Be

Quasi-free scattering reactions of ^{14}Be at 250 AMeV

RIBF Nishina Center, RIKEN, Japan

T. Lokotko, PhD thesis (Co-supervisor: Didier Beaumel)

III) Structure of ^{56}Ca and Magicity of ^{54}Ca

In-beam gamma spectroscopy of $^{53,56}Ca$ at 250 AMeV

RIBF Nishina Center, RIKEN, Japan

J. Liu, PhD thesis

Asymmetry Dependence of Nucleon Correlations

- Asymmetry Dependence of Nucleon Correlations by Single-nucleon Knockout of ^{30}Ne at 250 MeV/u (RIKEN)

papers in preparation

- Benchmark Reaction Mechanisms by Knockout of ^{14}O at 60 MeV/u (RCNP, Osaka University)

Analyzed by Y. Sun (PKU), Ph.D thesis

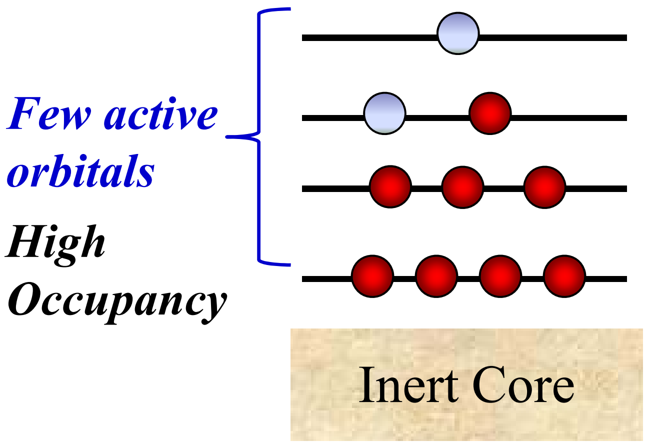
Neutron-Proton Correlations

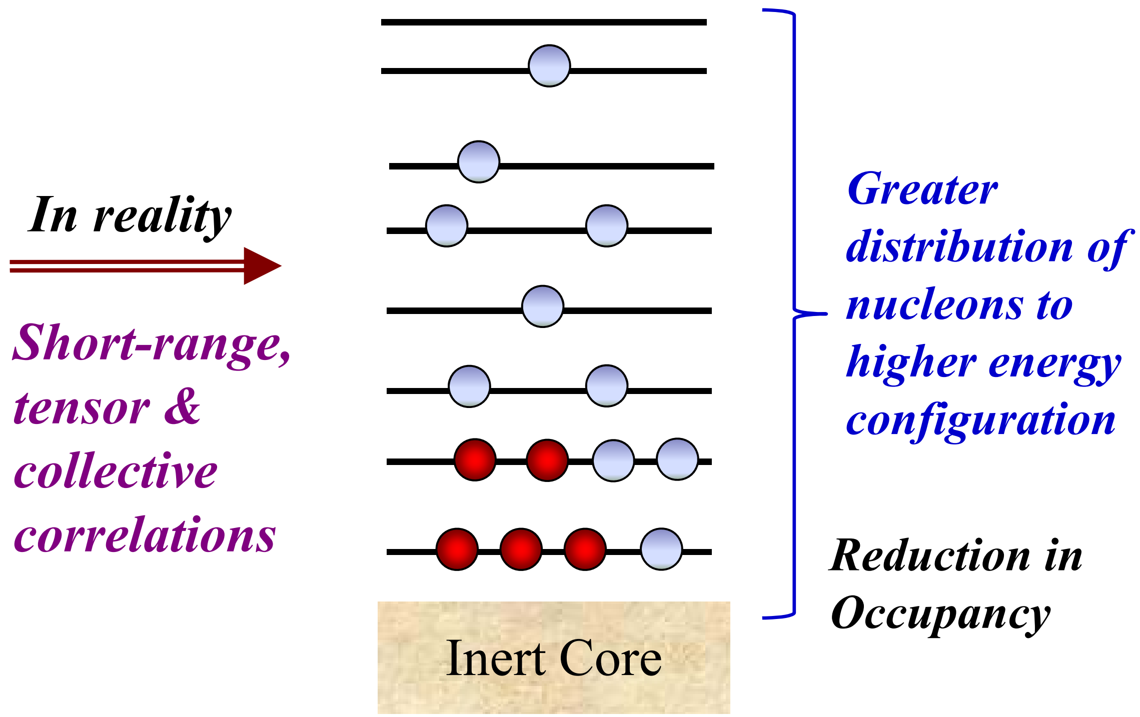
- Neutron-proton Pairing by Systematic Pair-nucleon Transfer Reactions of *sd*-shell Nuclei (RCNP) *Analyzed by Y. Ayyad (RCNP)*

- Neutron-Proton Correlations by first Exclusive pair-nucleon Knockout of ^{12}C at 200 MeV/u (RIKEN) *Analyzed by H. Liu (PKU/RIKEN), Ph.D thesis*

Nucleon Correlations

Truncated shell model space
+ effective interactions





<u>Probing the nuclear wave function</u>

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

Spectroscopic Factor (SF)

Cross Sections ✚ Reaction Model

➡ Spectroscopic Factors (expt)

Quantify Occupancy → Correlation Effects

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

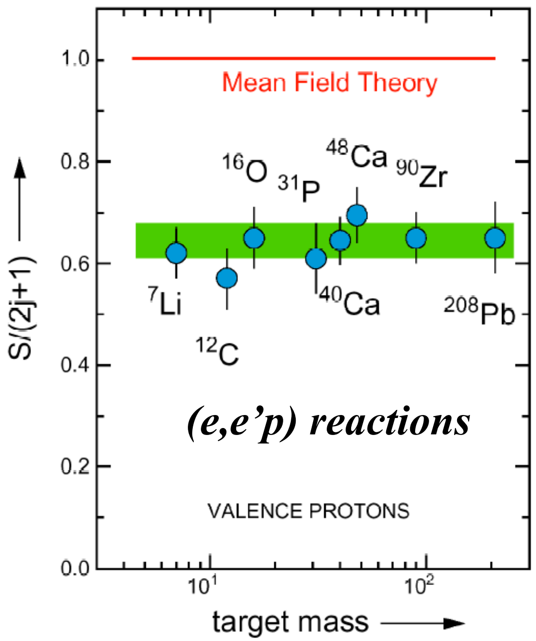
How good the effective interaction in Shell Model can describe the correlations ?

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

SM description is accurate

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

Some correlations missing in the interactions ?



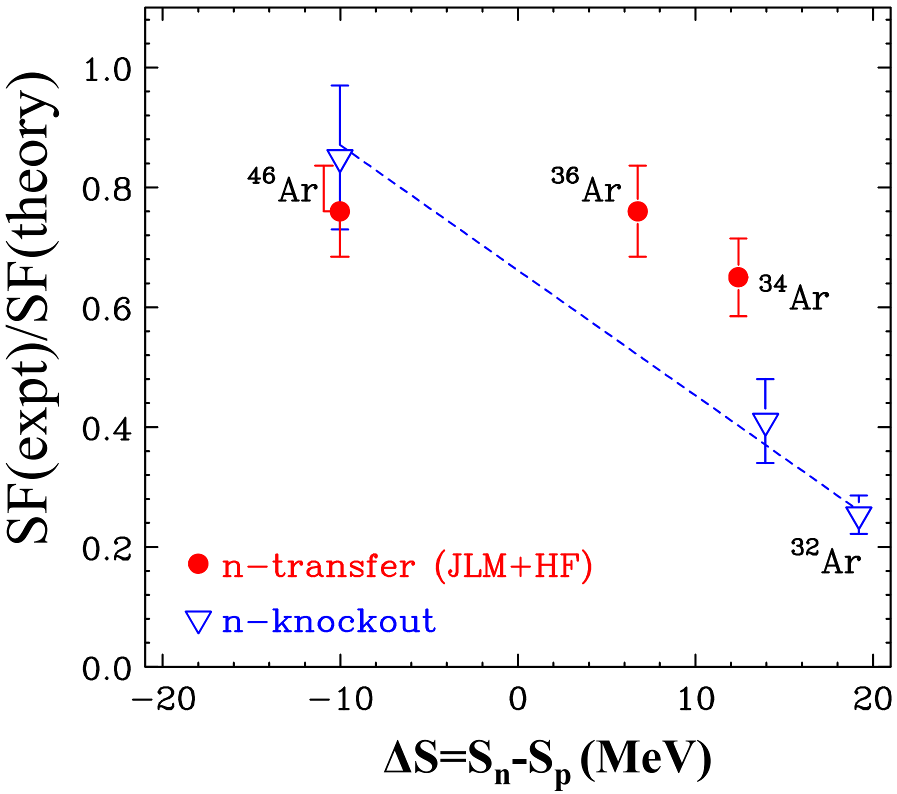
(e,e'p) – Stable nuclei (near closed shell)

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

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

Extend SF measurements to Exotic Nuclei !

Isospin Dependence of Shell Occupancies?



Q: Isospin Dependence ?

Knockout reactions: Yes & Strong

$^{32,34,46}Ar(^{9}Be,X)$ at ~ 70 A MeV

A. Gade et al., Phys. Rev. Lett. 93, 042501 (2004)
Phys. Rev. C 77, 044306 (2008) & reference therein

Transfer reactions: Weak

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

J. Lee et al., Phys. Rev. Lett 104, 112701 (2010)
Phys. Rev. C 83, 014606 (2011)

NSCL

Systematic difference between two probes !

Incompatibility → Incomplete understanding in underlying reaction mechanism

Transfer Reaction

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

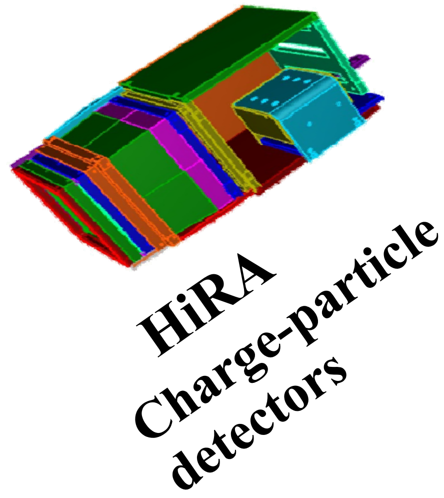
- same energy as knockout reactions for direct comparison

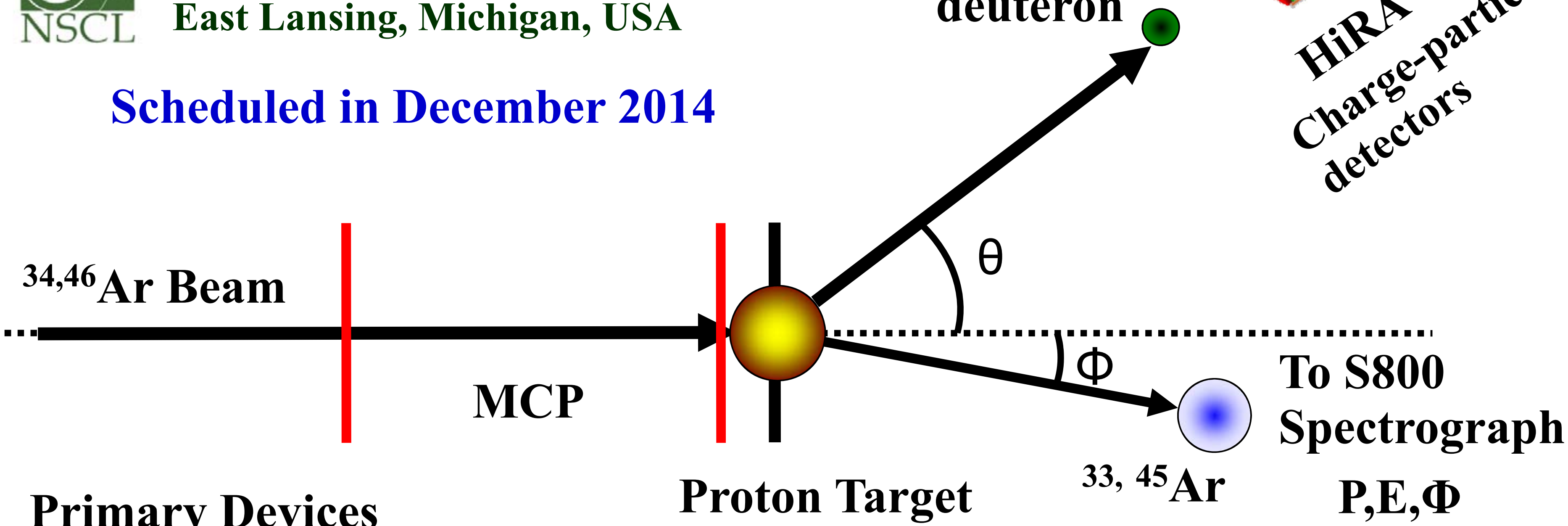
Transfer Reactions for Correlation Studies

$^{34,\,46}$Ar + p $\rightarrow$ d + $^{33,\,45}$Ar @ 70 MeV/u

National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, Michigan, USA

Scheduled in December 2014



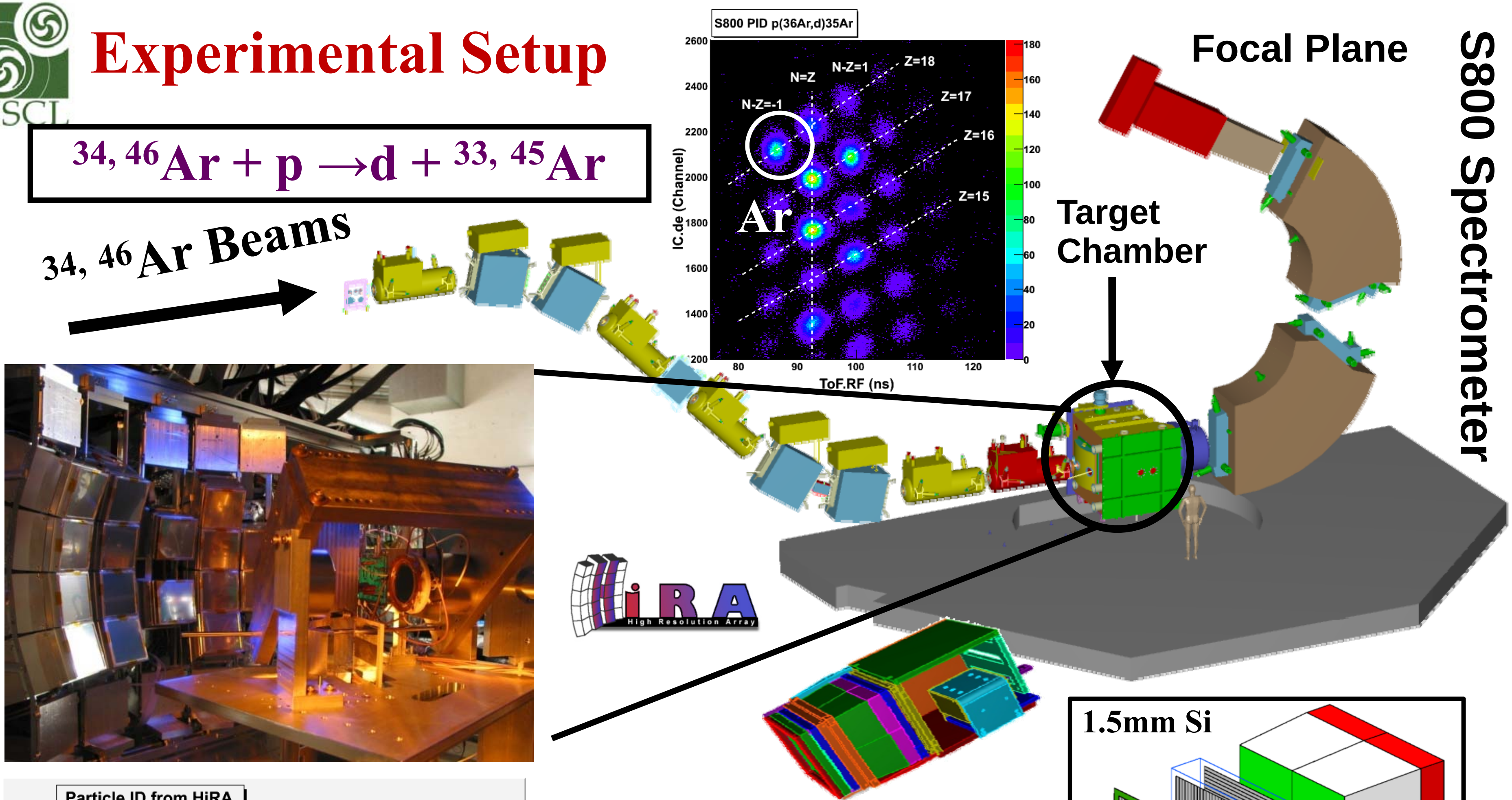


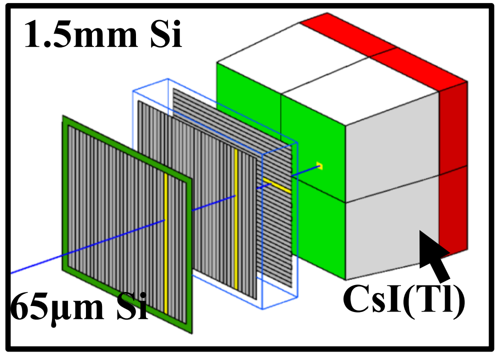
Primary Devices

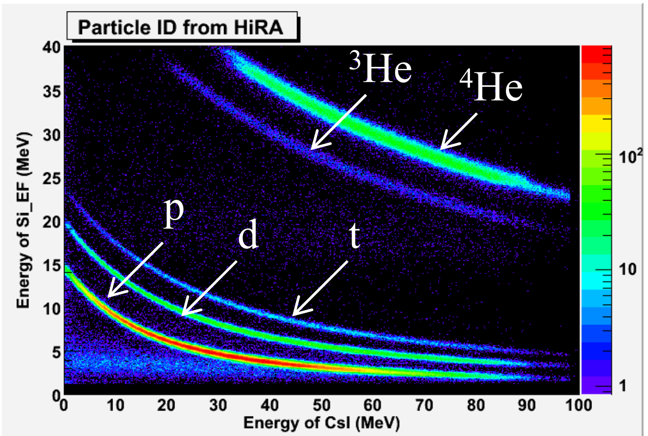
1. **High Resolution Array (HiRA)**
2. **S800 Spectrograph**
3. **Multi-Channel Plates (MCP)**

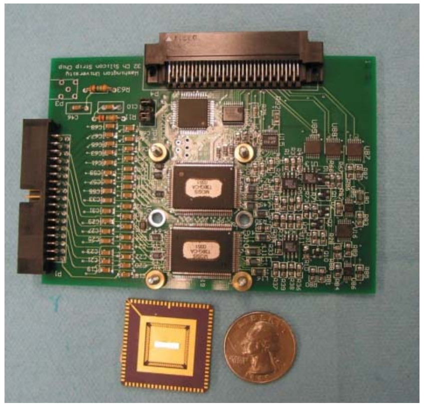
Experimental Setup

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



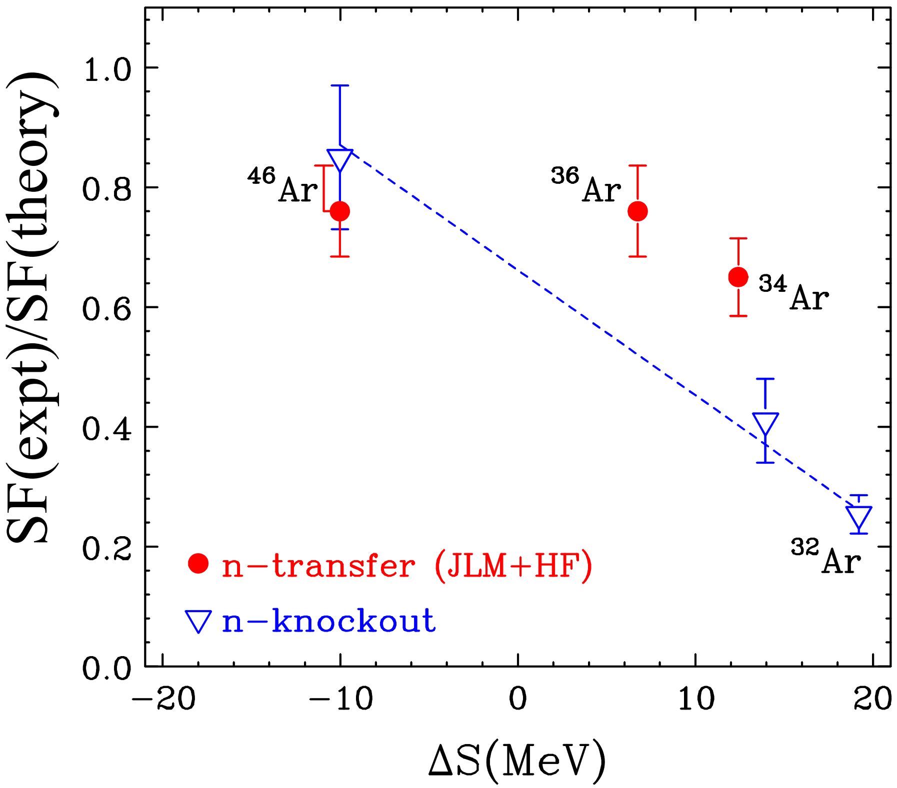






ASIC readout

Isospin Dependence of Shell Occupancies?



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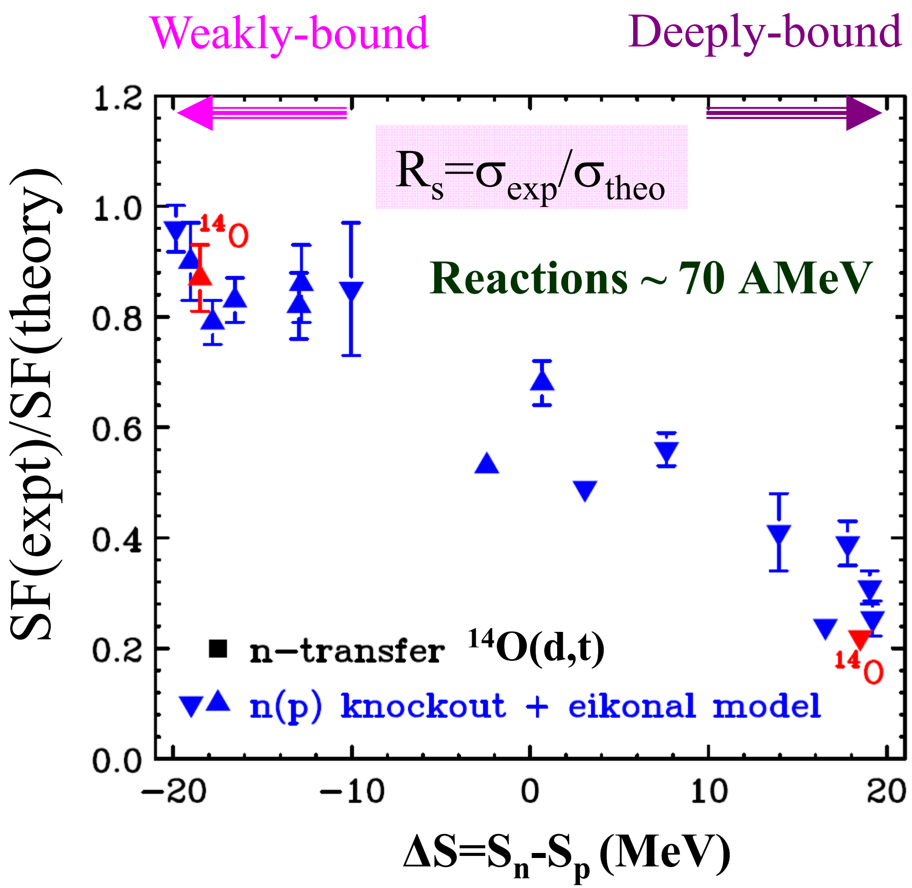
Transfer Reaction

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

- same energy as knockout reactions for direct comparison

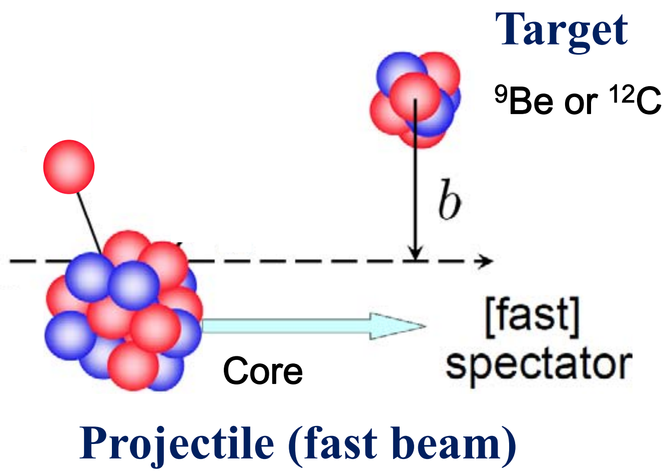
Knockout Reaction ?

Knockout Reaction Mechanism



Reaction Theory:
Eikonal & Sudden Approximations

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



NSCL, MSU - ^{14}O knockout at 60 MeV/A
F. Flavigny *et al.,* Phys. Rev. Lett. 108, 252501 (2012)

1. Reaction energy high enough ?

✓ Data at energies of 200-300 AMeV

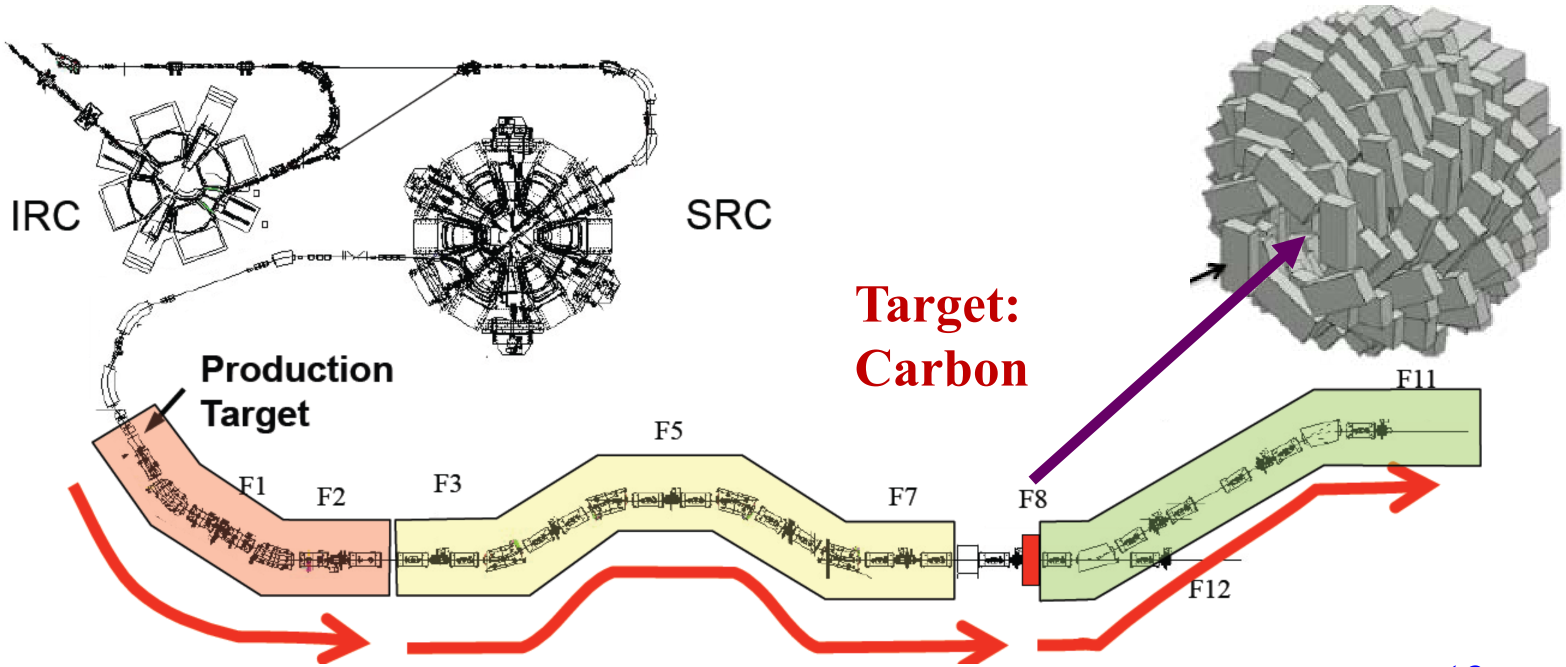
Spectroscopic information towards "Island of Inversion" using knockout reaction with in-beam gamma technique

Beam: ^{30}Ne @ ~ 250 A MeV

1n-knockout : $^{30}Ne \rightarrow {}^{29}Ne$

1p-knockout : $^{30}Ne \rightarrow {}^{29}F$

^{30}Ne: |ΔS| ~ 20 MeV



DALI2 (γ-ray detection)

BigRIPS (Beam PID)

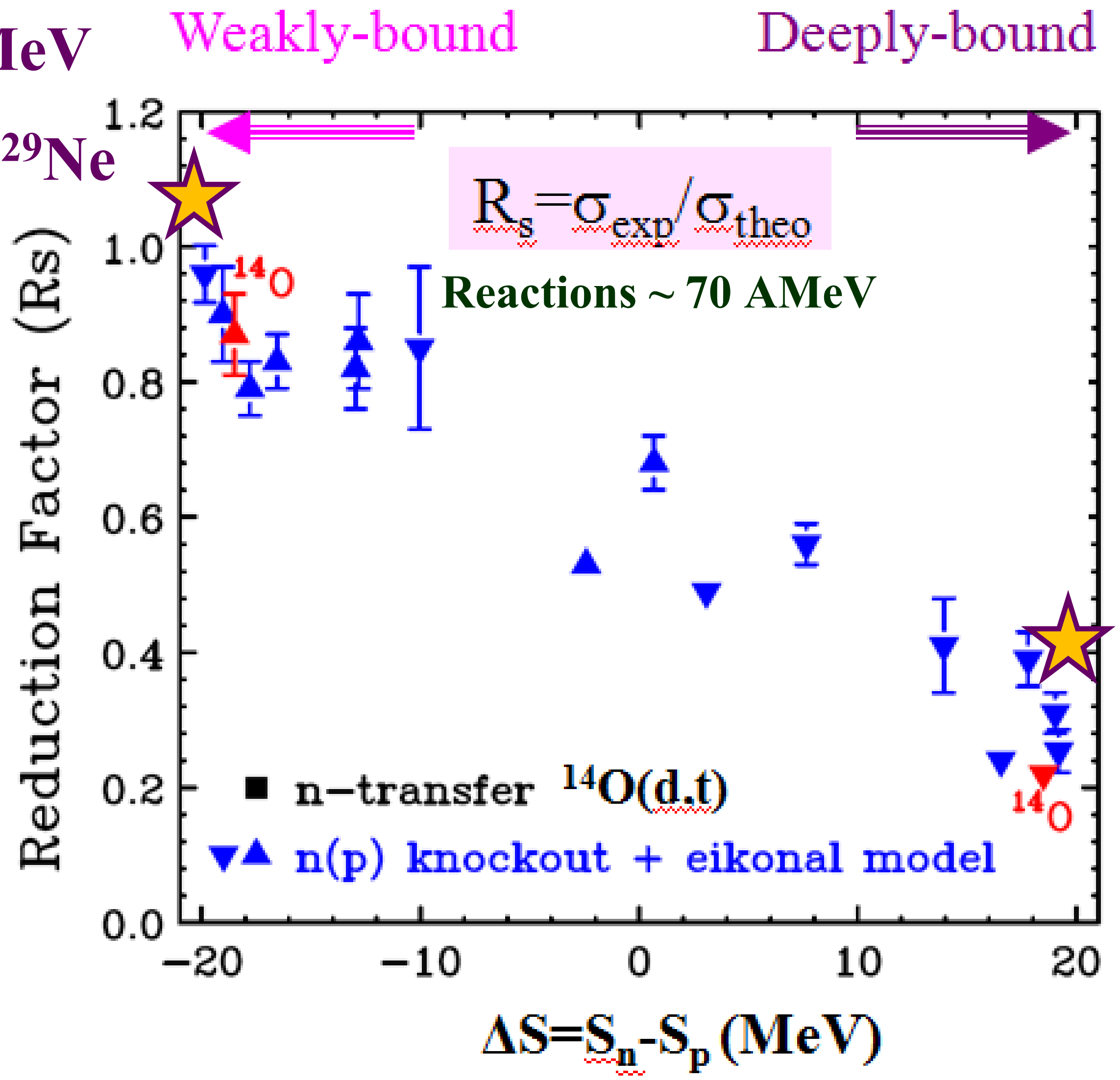
ZeroDegree (fragment PID & momentum measurement)

Energy Dependence ?

250 AMeV

$^{30}Ne \rightarrow ^{29}Ne$

analyzed by H. Liu



$^{30}Ne \rightarrow ^{29}F$

analyzed by P. Doornenbal

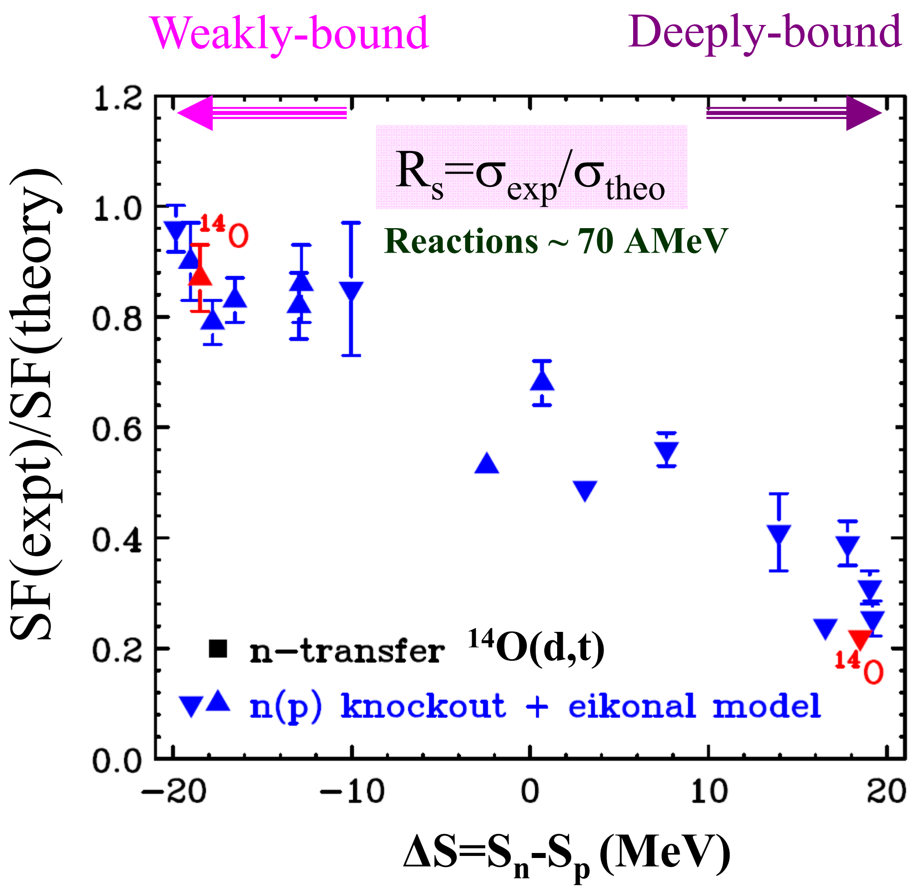
Reaction Calculations
K. Minomo, K. Ogata
(Eikonal Model)

Structure Calculations
Y. Utsuno (SM)
M. Kimura (AMD)

^{30}Ne: $|\Delta S| \sim 20$ MeV

Papers in preparation

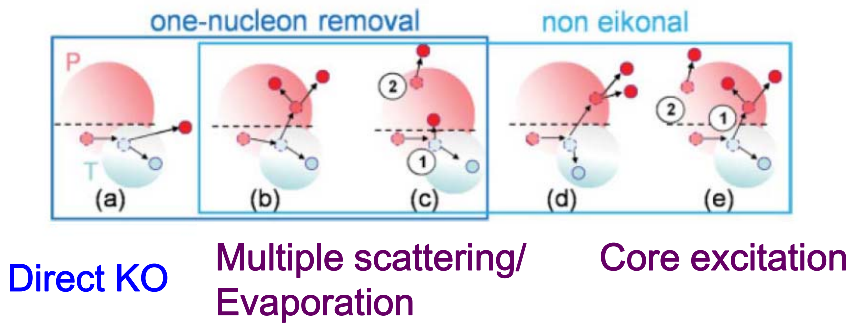
Knockout Reaction Mechanism



NSCL, MSU - ^{14}O knockout at 60 MeV/A
F. Flavigny , A. Obertelli *et al.,*
Phys. Rev. Lett. 108, 252501 (2012)

GANIL E569S – SPIRAL d(^{14}O,t) ^{13}O at 18 A MeV
F. Flavigny, A. Obertelli *et al.*
Phys. Rev. Lett. 110, 122503 (2013)

2. Inert-core ?



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

Intranuclear Cascade Model (*INC*)

Proj.		ℓj	C^2S	σ_{exp} (mb)	σ_{casc}	σ_{evap} (mb)	σ	σ_{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

INC: Significant core-excitation process depletes the one-neutron removal channel

Understanding the knockout reaction mechanism needed !

Study of Reaction Mechanism

Fully Exclusive Measurements of reaction products

大阪大学·核物理研究中心

Osaka University *Research Center for Nuclear Physics*

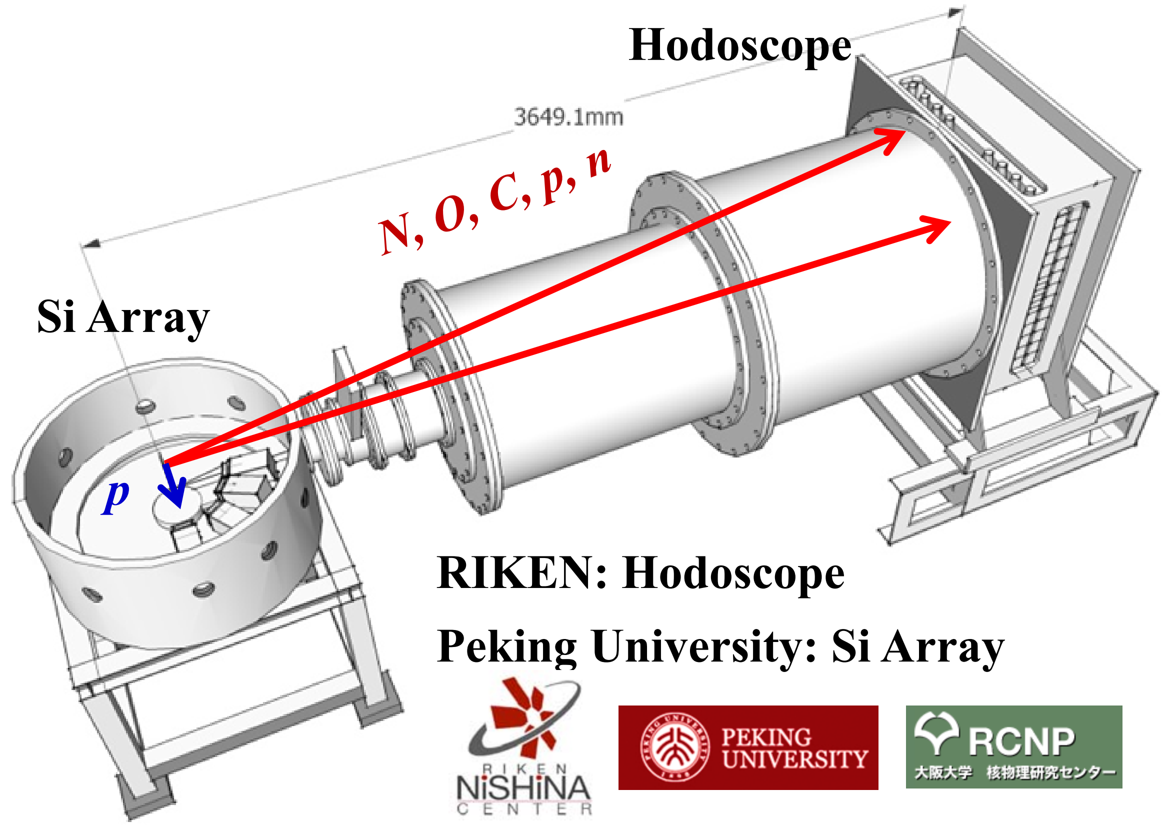
$^{14}O + ^{12}C \rightarrow ^{13}N + p$

$\rightarrow ^{13}O + n$

$\rightarrow ^{12}N + p$ (decay)

$\rightarrow ^{11}C + 2p$ (decay)

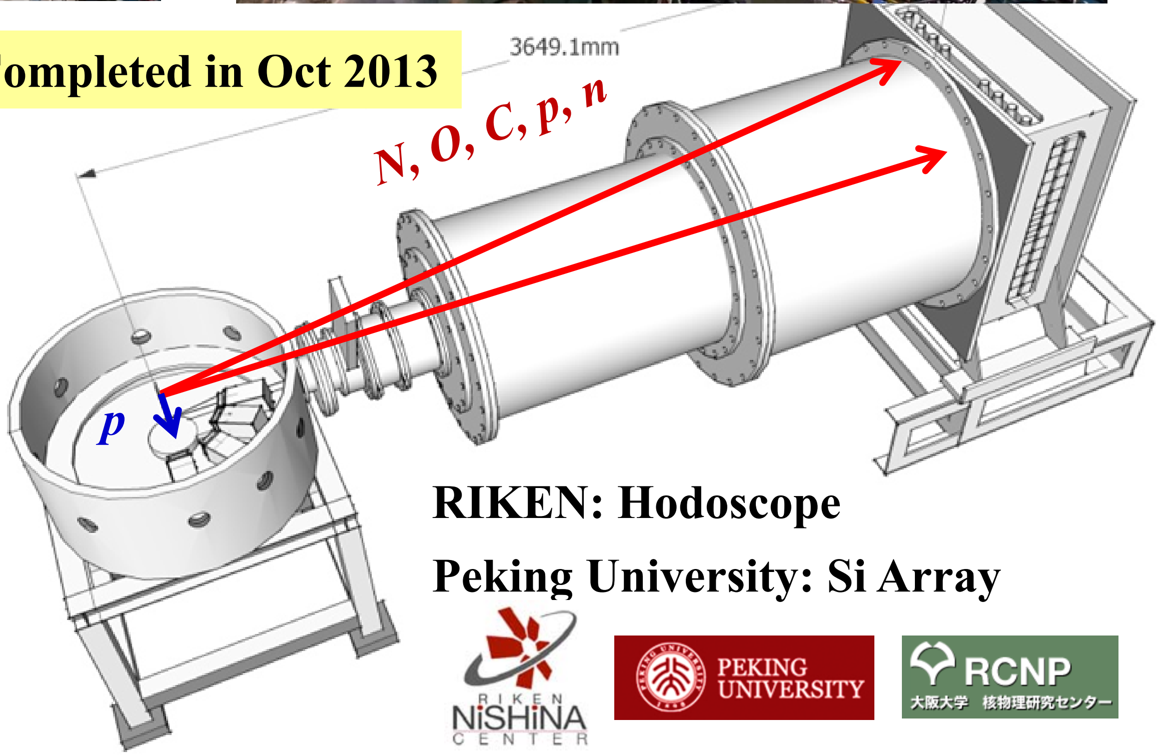
EN-Course Beam line



RIKEN: Hodoscope

Peking University: Si Array

Completed in Oct 2013



RIKEN: Hodoscope

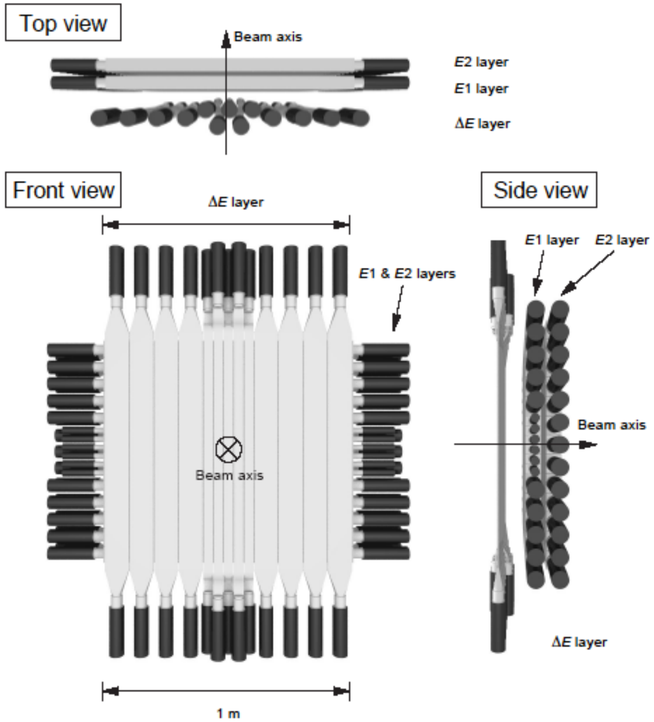
Peking University: Si Array

RIKEN NiSHiNA CENTER

PEKING UNIVERSITY

RCNP 大阪大学 核物理研究センター

Hodoscope and Tube Chamber



T. Motobayashi &
Rikkyo University group

42 Scintillators (1-meter long)

3 layers (active area of 1x1 m^2)

ΔE : 5 mm thick (13 bars)

E1, E2: 60 mm thick

Between Target to Hodoscope:
3.6 meters in vacuum
→ Position, Timing Eenergy resolution

Hodoscope Acceptance: 0°-7°

Data in Analysis
Y. Sun (PKU), Ph.D Thesis

Asymmetry Dependence of Nucleon Correlations

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Neutron-Proton Pair Correlations

In nuclei: 4 types of Pairs

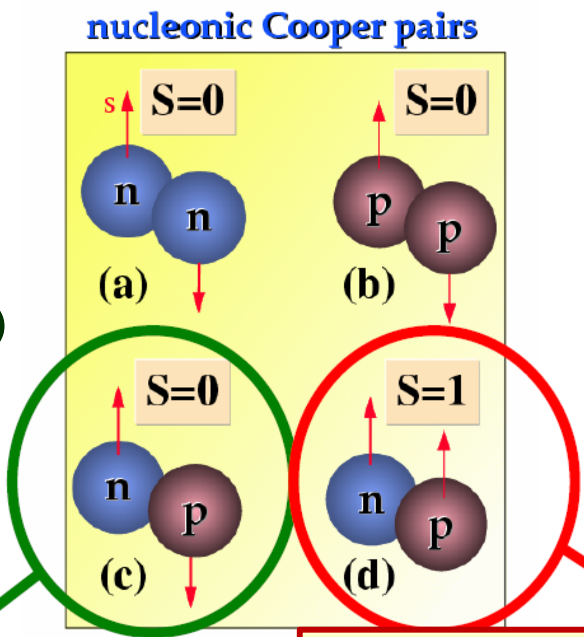
Isovector (T=1, S=0) nn, pp, np pair

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 !



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

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

Long-standing open 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 ?**

Two-nucleon Transfer Reactions

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

Deuteron Transfer in $N = Z$ Nuclei

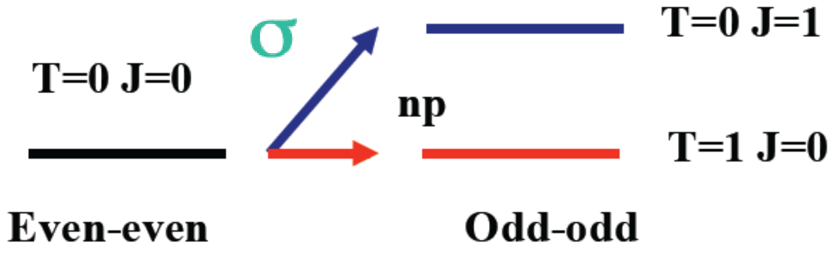
P. Van Isacker,[1] D. D. Warner,[2] and A. Frank[3]
[1]*Grand Accélérateur National d'Ions Lourds, B.P. 55027, F-14076 Caen Cedex 5, France*
[2]*CCLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[3]*Instituto de Ciencias Nucleares, UNAM, Apdo. Postal 70-543, 04510 México, D.F. Mexico*
(Received 14 September 2004; published 29 April 2005)

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

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	$N_b + 1$



<u>Reactions</u>

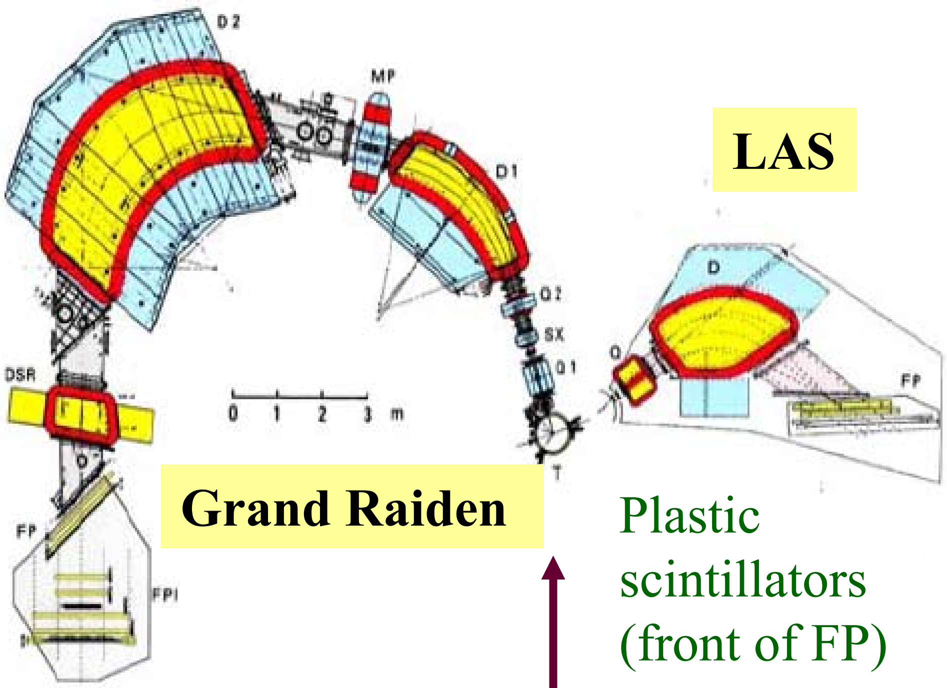
(p, ^{3}He), (^{3}He,p)	ΔT=0,1
(d,α), (α,d)	ΔT=0
(α, ^{6}Li), (^{6}Li,α)	ΔT=0

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

Systematic studies of neutron-proton pairing in *sd*-shell nuclei using (*p*,^{3}*He*) and (^{3}*He*,*p*) transfer reactions



Plastic scintillators (front of FP)

Two MWDCs -- position

One plastic scintillator
-- E, TOF for PID

^{3}He beam at 25 MeV

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

Proton beam at 65 MeV

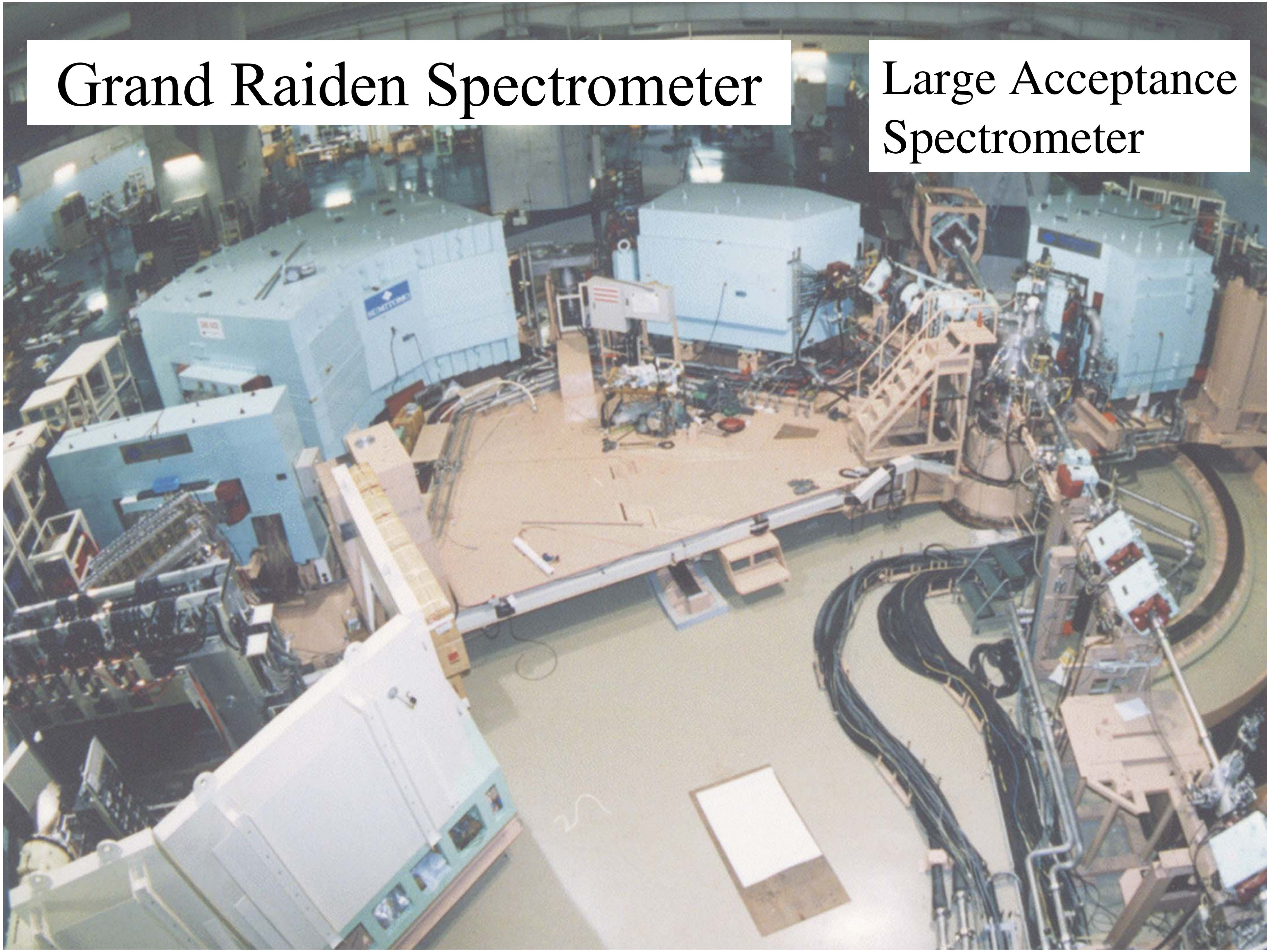
^{24}Mg(p,^{3}He),^{28}Si(p,^{3}He),^{40}Ca(p,^{3}He)

also 2n-transfer and 1n-transfer data

Grand Raiden → recoil particle

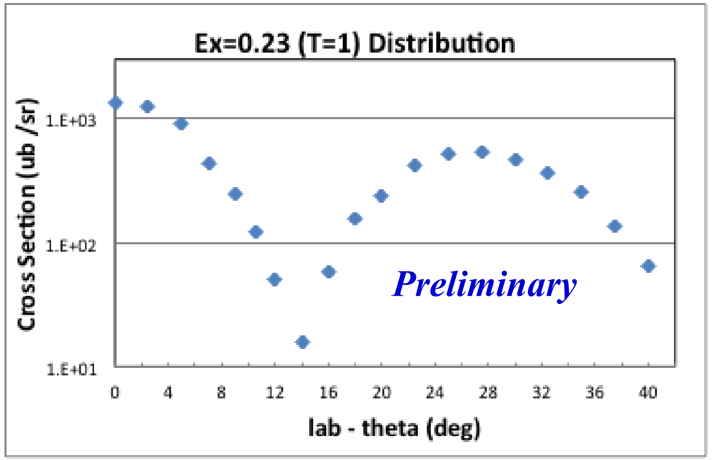
LAS → elastic scattering reaction
(beam normalization & target thickness measurement)

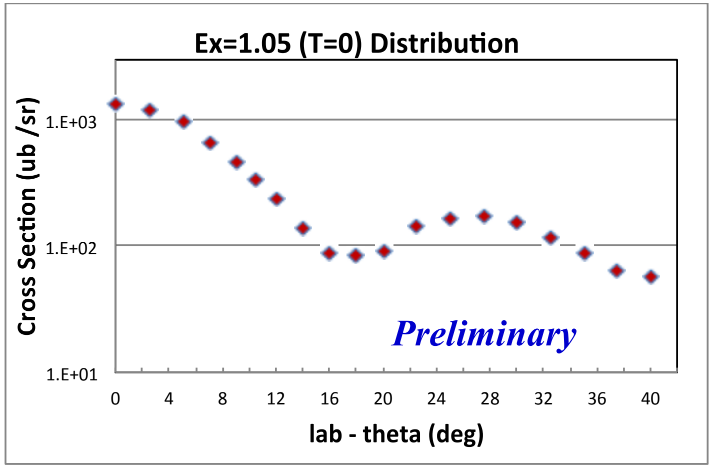
65 MeV proton / 25 MeV ^{3}He beams from injector AVF cyclotron (bypass Ring-Cyclotron)


Grand Raiden Spectrometer
Large Acceptance Spectrometer

Systematic studies of neutron-proton pairing in *sd*-shell nuclei using (*p*,^{3}*He*) and (^{3}*He*,*p*) transfer reactions

^{24}Mg (^{3}He,p) at 25MeV





Data Analysis by Y. Ayyad (RCNP)

N=Z nuclei in sd-shell

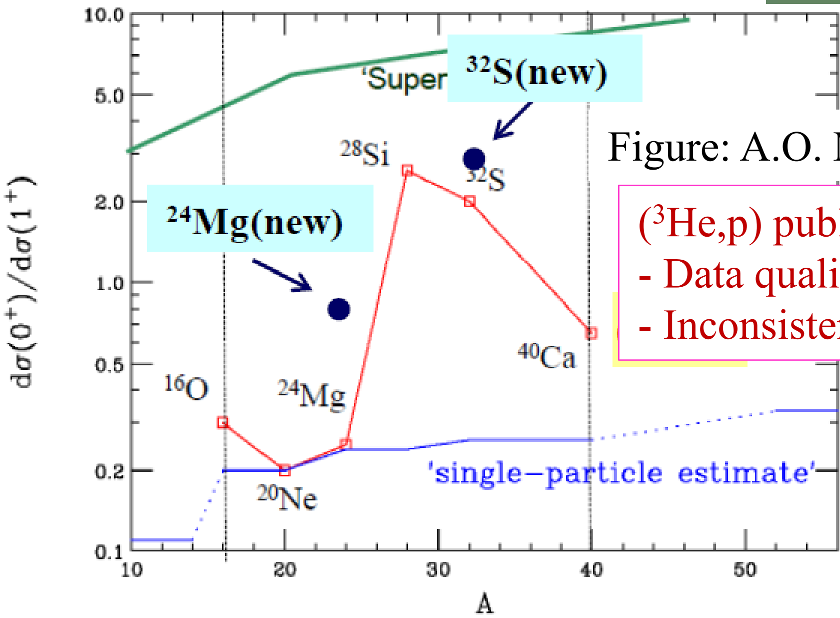


Figure: A.O. Macchiavelli

(^{3}He,p) published data
- Data quality
- Inconsistency

Reaction Model (G. Potel (MSU)):

Calc. of absolute (p,t) **cross sections achieved:**
- Proper pairing interaction
- Multistep (successive, simultaneous)

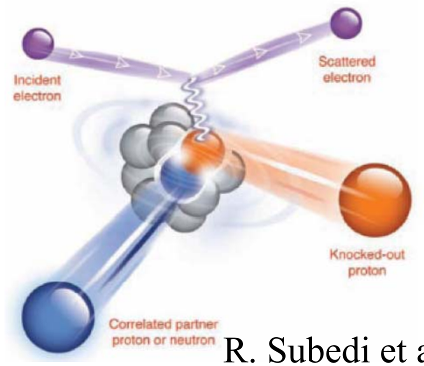
G. Potel et al., Phys. Rev. Lett 107, 092501

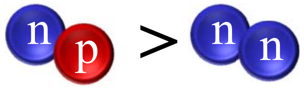
Extend to np-transfer with T=0 pairing included

"Unusual" neutron-proton Correlations in ^{12}C

$^{12}C(e,e'pN)$ @ 4.627 GeV

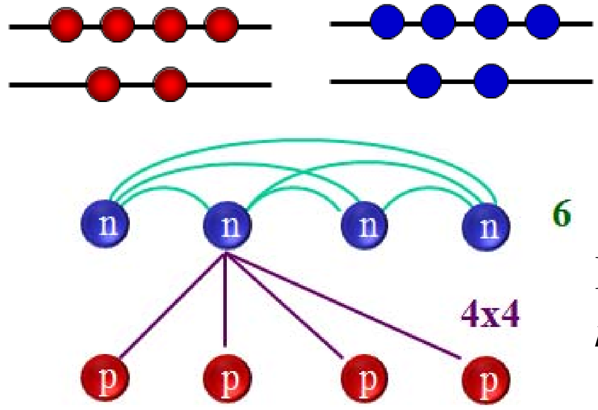
18 times





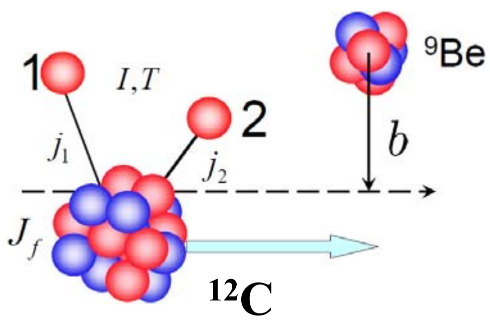
Jefferson Lab. (US)

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



Pair counting
***np/nn* Ratio: 2.7**

$^{12}C + ^{9}Be$ @ 200 MeV/*u*



Reaction Products:
^{10}B (-*np*), ^{10}C (-2*n*), ^{10}Be (-2*p*)

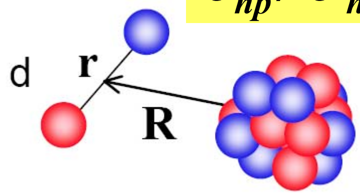
Few Hundred MeV ?

18 times vs 2.4 times
→ Underlying Physics ?

Energy – 100 times different

$^{12}C(p,^{3}He)$, $^{12}C(p,t)$ @ 40 MeV

σ_{np}/σ_{nn}: 2.4 times



M. Yasue et al., J. Phys. Soc. Jap. 42, 367 (1977).

First final-state-exclusive *np* knockout data

Multi-particle Detector Systems

BDC: Tracking of ^{12}C Beams

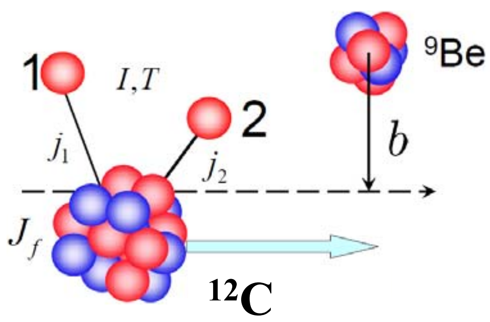
DALI2 NaI: gamma rays

NEBULA: neutrons

FDC: Tracking of **^{10}B ,^{10}C, ^{10}Be**

Hodoscope: **^{10}B ,^{10}C, ^{10}Be**

^{12}C + ^{9}Be @ 200 MeV/*u*



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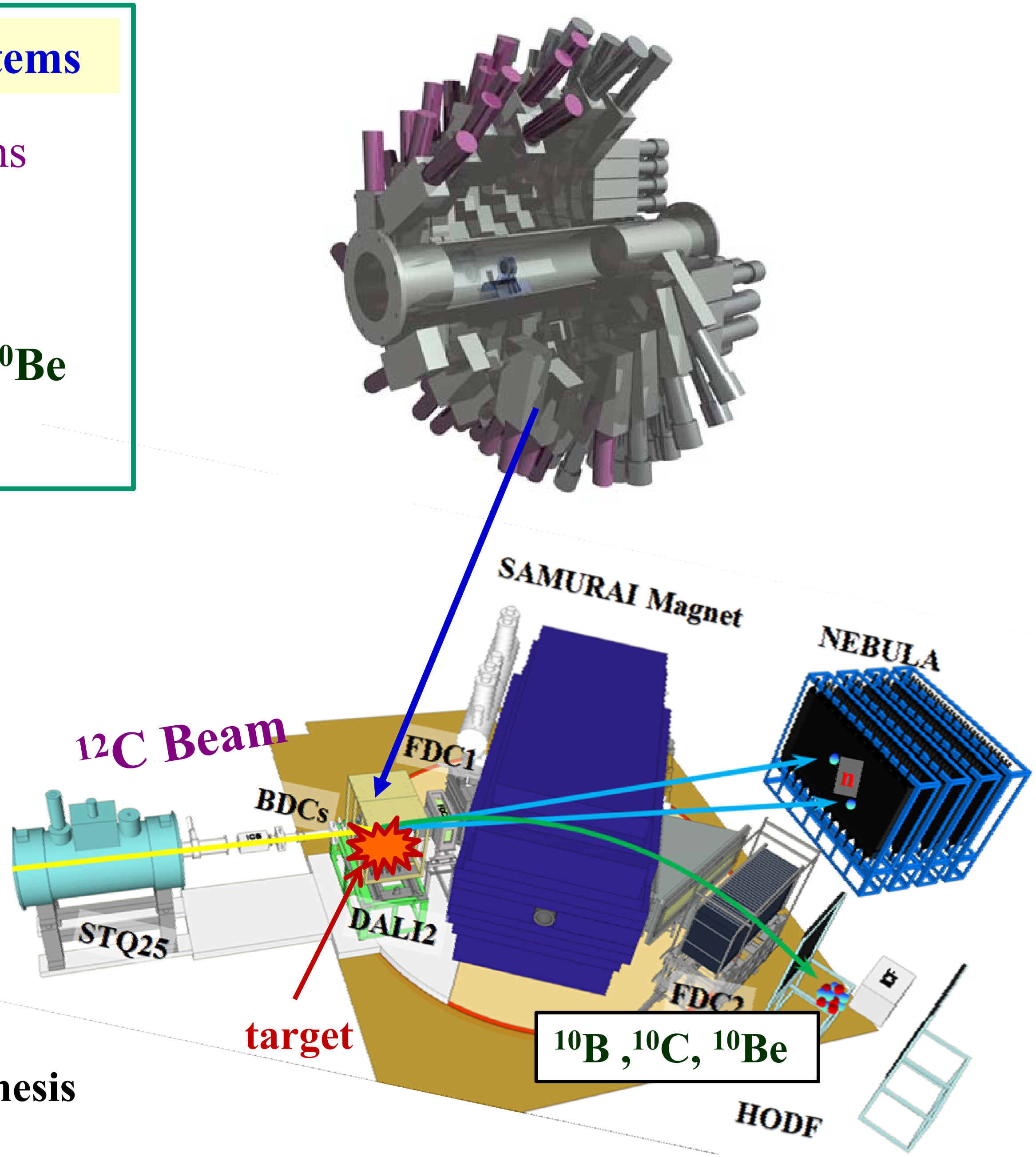
^{10}B (-*np*), ^{10}C (-2*n*), ^{10}Be (-2*p*)

H. Liu (PKU/RIKEN), Ph.D Thesis

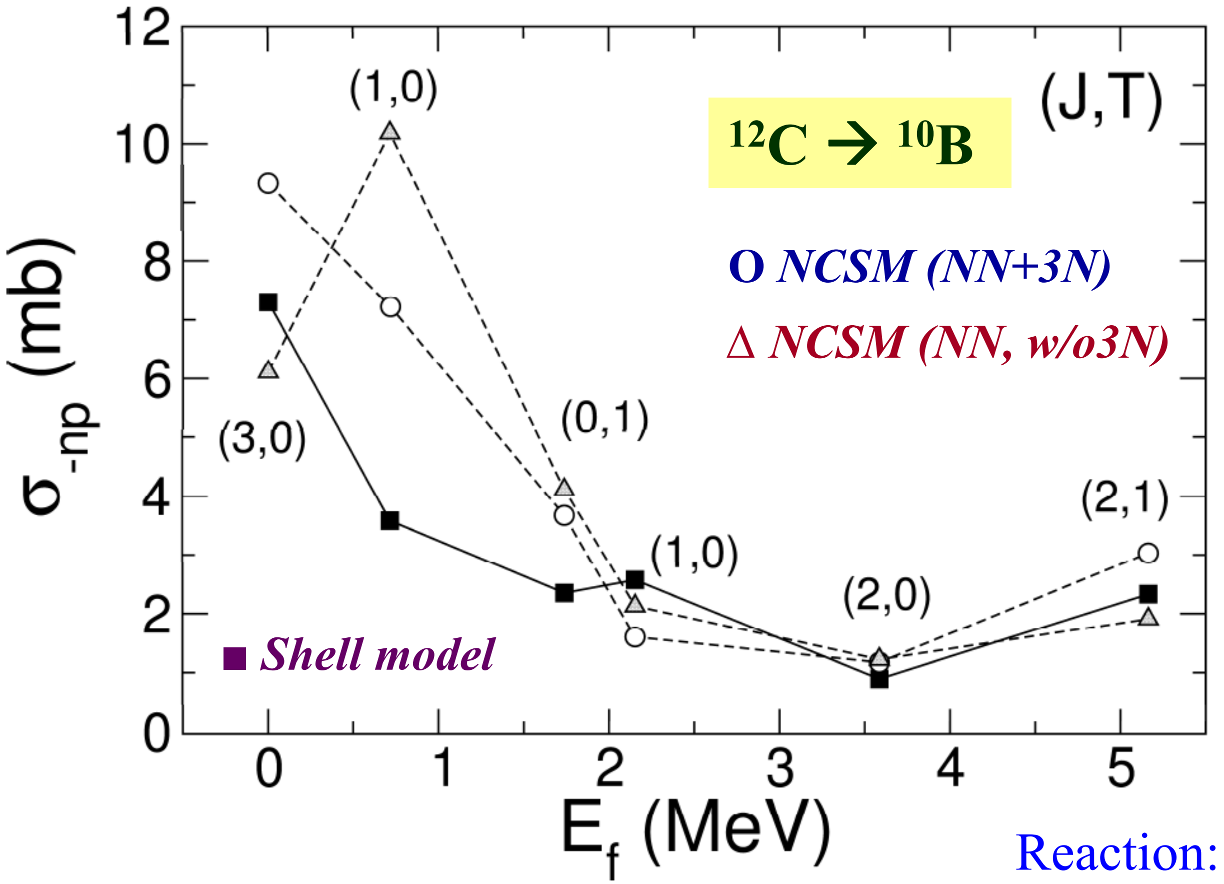


First final-state-exclusive *np* knockout data

np-Correlations & 3-body Force

No-core shell model (NCSM) *ab initio* calculations
(including realistic 2-body interaction and 3-body forces)

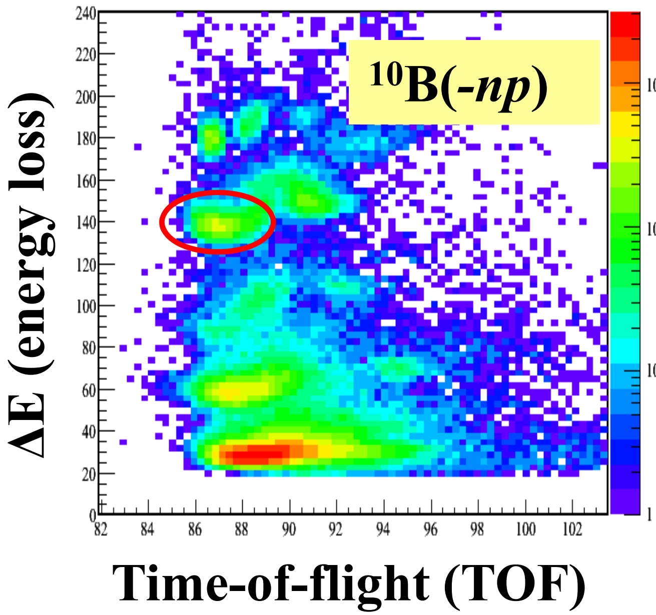
E. C. Simpson, P. Navrátil, R. Roth, and J. A. Tostevin et. al., PRC 86, 054609(2012)

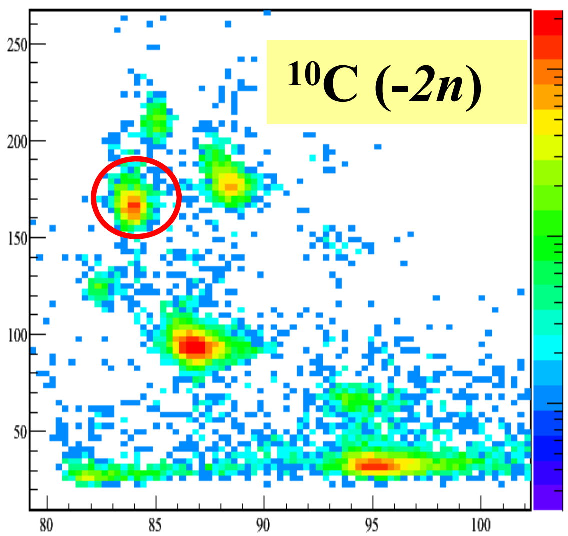


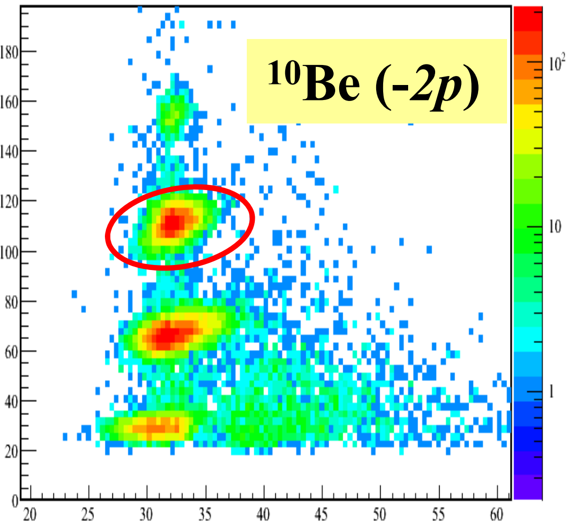
Reaction: Eikonal Model

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

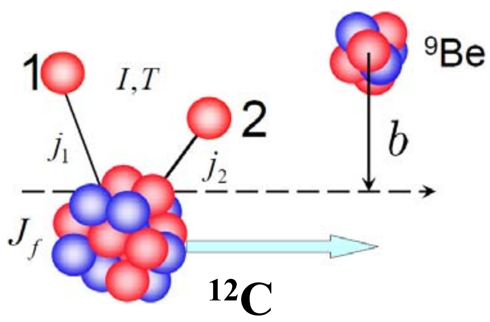
First final-state-exclusive *np* knockout data

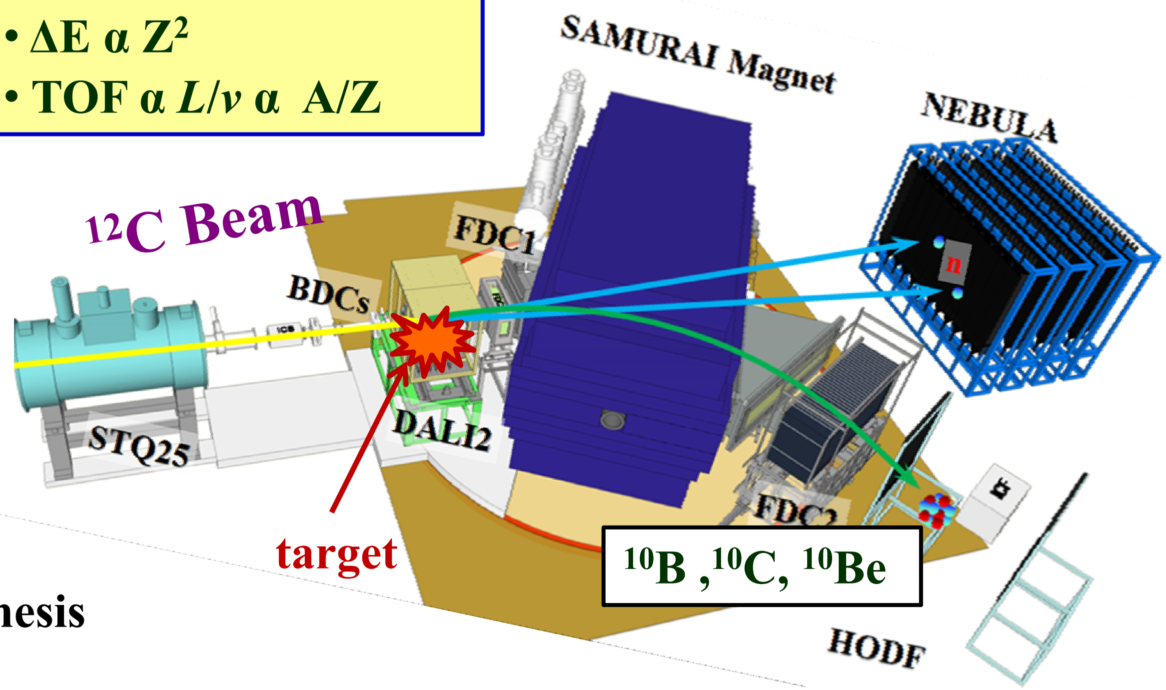






Particle Identification
- ΔE α Z^2
- TOF α L/v α A/Z





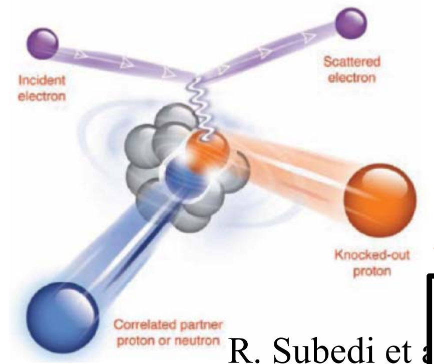
Reaction Products:
^{10}B (-*np*), ^{10}C (-2*n*), ^{10}Be (-2*p*)

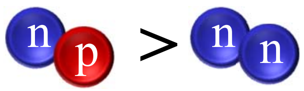
H. Liu (PKU/RIKEN), Ph.D Thesis

“Unusual” neutron-proton Correlations in ^{12}C

$^{12}C(e,e'pN)$ @ 4.627 GeV

18 times

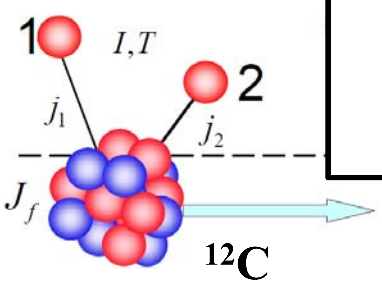


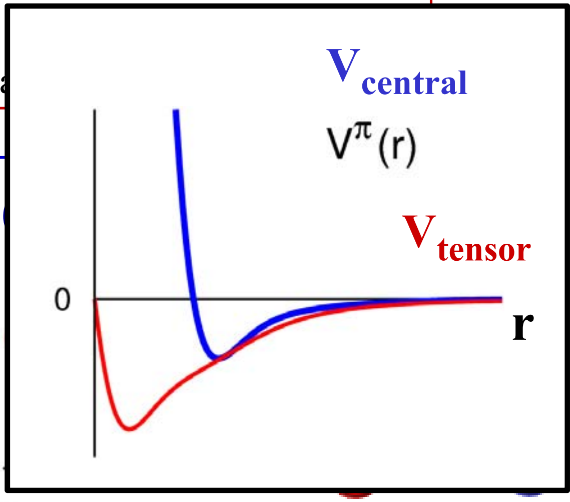


Jefferson Lab. (US)

R. Subedi et a

^{12}C + ^{9}Be @ 20





~ 5 times !

H. Liu (PKU/RIKEN), Ph.D Thesis

Preliminary Results

J.M. Kidd et al., PRC 37, 2613 (1988): Ratio: ~ 6 (250AMeV)

D.L. Olsonet al., PRC 28 ,1062 (1983): Ratio: ~ 4 (2.1 GeV)

Ratio is Energy Dependent!

Higher energy → Pick-up Pairs with higher relative momentum

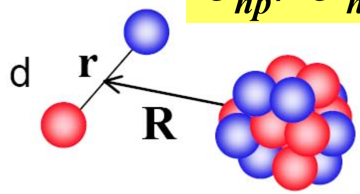
Behavior of T=0 *np*-correlations: function of pair relative momentum !

Larger ΔP → Smaller Δx

Properties of Tensor Interaction at Different Ranges Determined

$^{12}C(p,{}^{3}He)$, $^{12}C(p,t)$ @ 40 MeV

$\sigma_{np}/\sigma_{nn} \sim$ 2.4 times

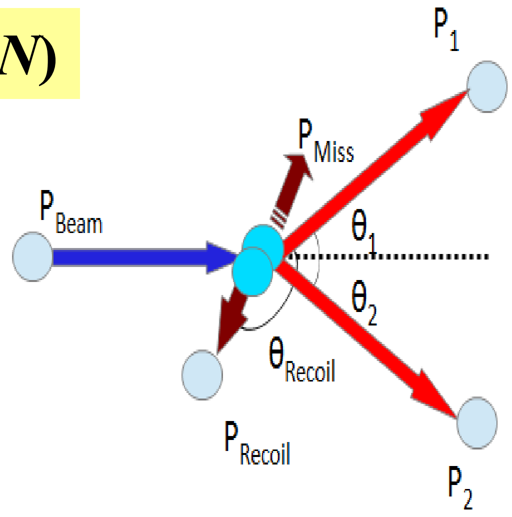


M. Yasue et al., J. Phys. Soc. Jap. 42, 367 (1977).

Unified Probe to Cover the Entire Ranges

How about using proton beam ?

$^{12}C(p,ppN)$



A variety of incident energies (MeV-GeV)

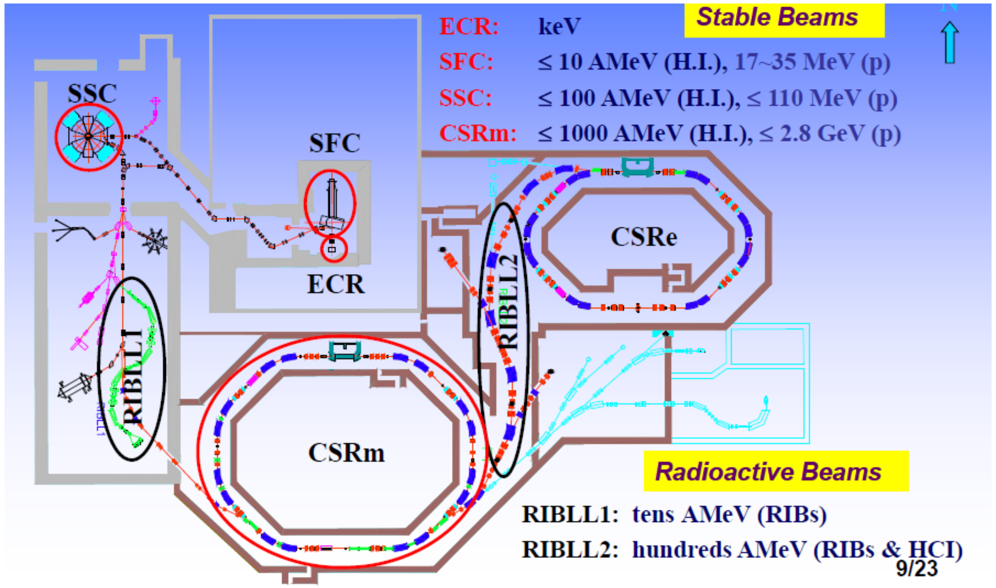
Simple Measurement → Direct and Clear Probe to SRC

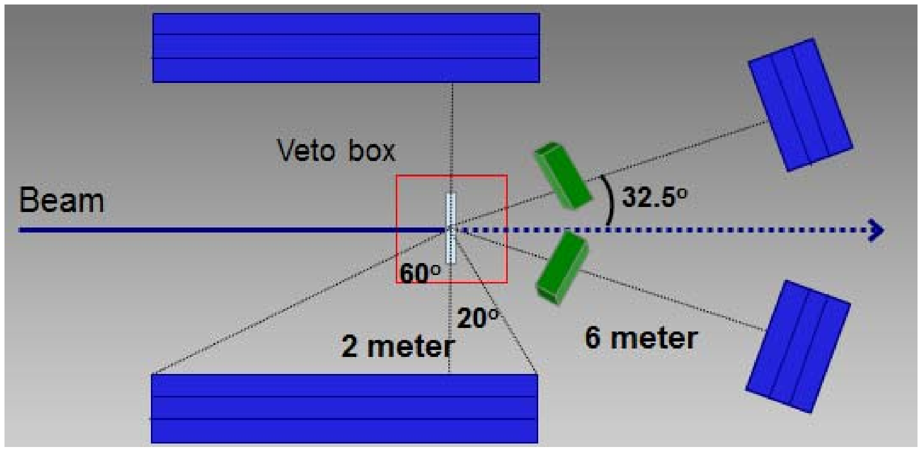
Larger Production Yield → More Statistics

Future: Proton Target & Radioactive Beam

中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences

up to 2.8 GeV





E. Piasetzky M. Strikman, J. Lee

Experimental Program: ^{12}C, ^{40}Ca, ^{48}Ca, ^{208}Pb, d (800 MeV – 2.8 GeV)

Summary I

Asymmetry Dependence of Nucleon Correlations

Single-nucleon Knockout of ^{30}Ne at 250 MeV/u (RIKEN)

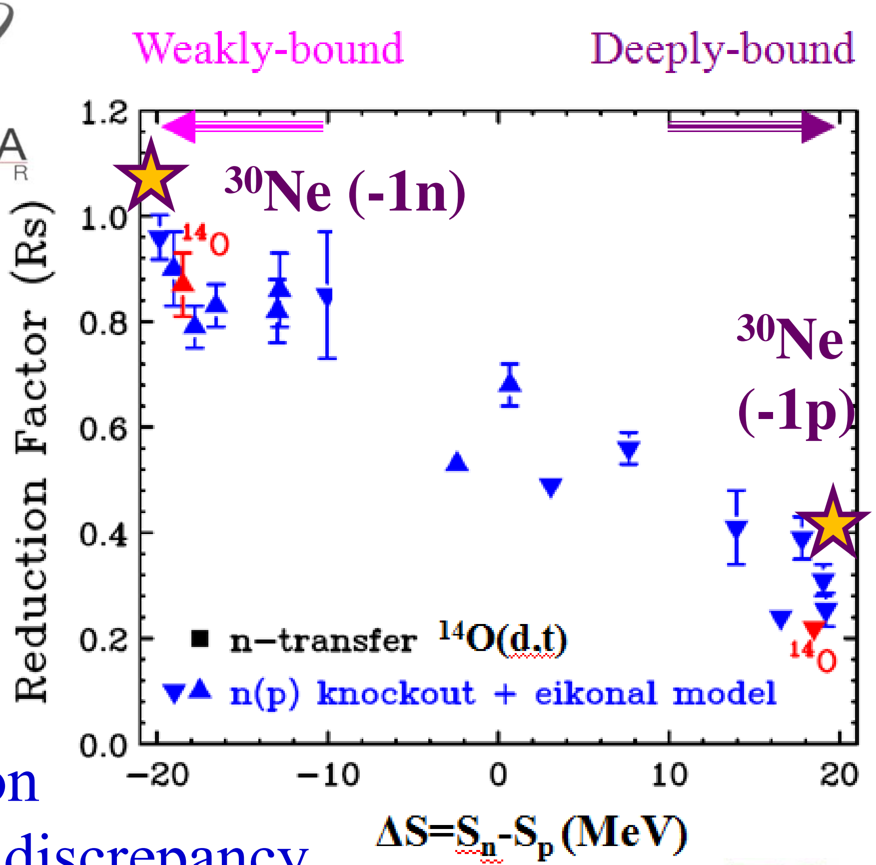
→Dependence not due to the invalidity of Reaction Model at "low" energy ~ 70 AMeV

papers in preparation

Fully Exclusive Knockout Reaction on ^{14}O at 60 AMeV

→ Detailed Examination of Reaction Mechanism to understand origin of discrepancy between transfer and knockout reactions

Y. Sun (PKU), Ph.D thesis



Transfer ^{34,46}Ar(p,d) at 70AMeV

(Scheduled Dec 2014)

RIKEN RIBF31 Collaborators:

One Nucleon Konckout Reaction on ^{30}Ne

RIKEN H. Liu, J. Lee, P. Doornenbal, H. Scheit, S. Takeuchi, N. Aoi, K. Li, M. Matsushita1, D. Steppenbeck1, H. Wang, H. Baba, E. Ideguchi,, T.Motobayashi, H. Sakurai, M. Takechi, Y. Togano

東京工業大学 Tokyo Institute of Technology

Tokyo Tech.
Y. Kondo, N. Kobayashi

CNS/ Unvi. Of Tokyo
S. Michimasa

Theory Collaboration:

RCNP 大阪大学 核物理研究センター

RCNP/Osaka University
K. Minomo, K, Ogata

HOKKAIDO UNIVERSITY

Hokkaido University
M. Kimura

JAEA

JAEA
Y. Utsuno

UNIVERSITY OF SURREY

Univ. of Surrey
J. A. Tostevin, E.C. Simpson

RCNP E390 Collaborators:

Understanding Nucleon Stripping Reaction Mechanisms from Exotic Nuclei at Intermediate Energy

RIKEN
J. Lee, H . Liu, G. Lorusso, S. Nishimura, S. Takeuchi, J. Wu, Z. Xu

Peking University
Y. Ye, J. Chen, Y. Ge, Z. Li, J. Lou, R. Qiao, Y. Sun

RCNP
N. Aoi, Y. Ayyad, T. Hashimoto, E. Ideguchi, H.J. Ong, J. Tanaka, M. Tanaka, T. Trong, H. Suzuki, T. Yamamoto

Dep. Of Physics, Kyoto Univ.
T. Kawabata, T. Furono

CEA Saclay, France
A. Obertelli

INFN, Italy
F. Cappuzzello, M. Cavallaro

Theoretical Group
C. Bertulani (Texas), R. Crespo (Lisboa), K. Ogata (RCNP)

Summary II

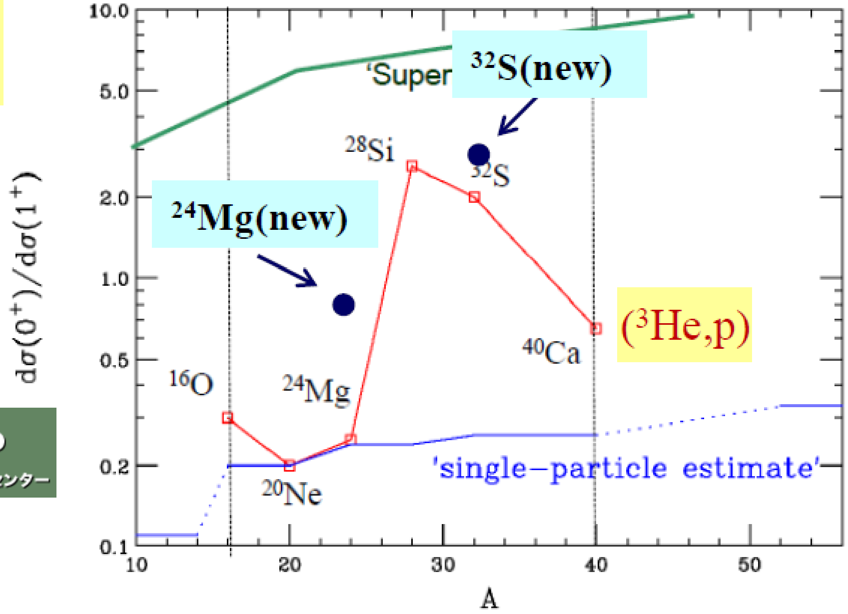
Neutron-Proton Correlations

np-pair and *nn*-pair Transfer Reactions of *sd*-shell Nuclei

→Systematic Study of Character & Interplay of T=0 and T=1 *np*-pairing

Analyzed by Y. Ayyad (RCNP)

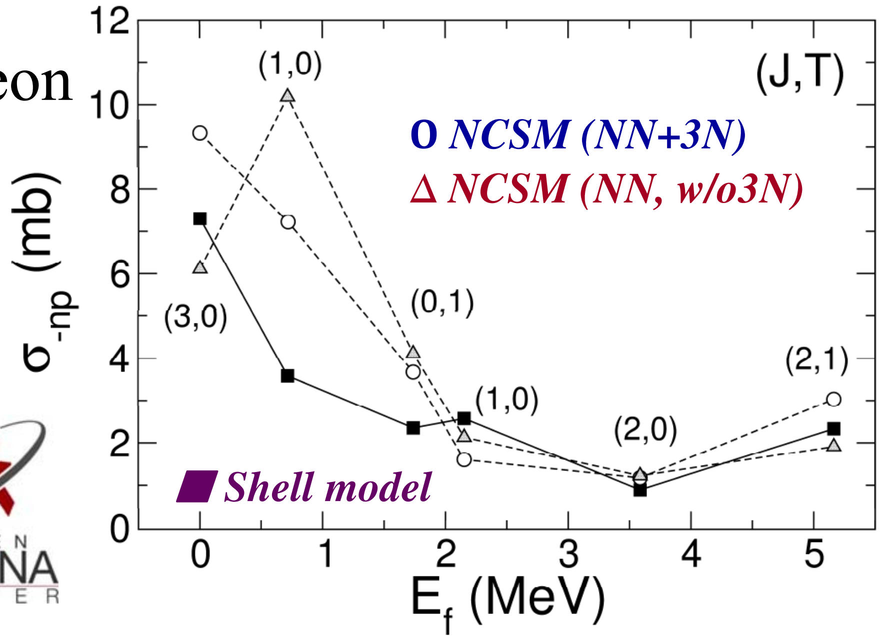
N=Z nuclei in sd-shell



First Final-state Exclusive pair-nucleon Knockout of ^{12}C at 200 AMeV

→ Neutron-Proton Correlations & 3body-Force in N=Z nuclei

H. Liu (PKU/RIKEN), Ph.D thesis



RCNP E365 Collaborators:

Systematic studies of neutron-proton pairing in *sd*-shell nuclei using (*p*,^{3}*He*) and (^{3}*He*,*p*) transfer reactions

RIKEN
J. Lee, Z, Li, H. Liu, J. Zenihiro

LLNL
I. J. Thompson

LBNL
A.O. Macchiavelli, P. Fallon

IPN Orsay
D. Beaumel

RCNP, Osaka U.
N. Aoi, Y. Ayyad
Y. Fujita, K. Hatanaka,
K. Miki, H. J. Ong,
T. Suzuki, A. Tamii,
Y. Yasuda

Dep. Phys., Osaka Univ.
H. Fujita

CNS, Univ. of Tokyo
H. Matsubara

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

Science Faculty, Istanbul Univ.
E. Ganioglu, G. Susoy

Theory Collaboration:
A. Brown , G. Potel

RIKEN NP1206-SAMURAI10 Collaborators:

Study of Neutron-Proton Correlation & 3N-Force in N=Z nuclei

RIKEN J. Lee, H. Liu, P. Doornenbal, N. Inabe, T. Isobe, T. kubo, S. Kubono, T. Motobayashi, M. Nishimura, H. Otsu, H. Sakurai, H. Sato, Y. Shimizu, S. Takeuchi, H. Wang, K. Yoneda

Tokyo Tech.
Y. Kondo, T. Nakamura, S. Nishi, R. Tanaka

Tohoku Univ.
T. Kobayashi

RCNP, Osaka U.
N. Aoi

Univ. of Kyoto
Y. Matsuda

LBNL
A.O. Macchiavelli, P. Fallon

CNS/ Unvi. Of Tokyo
M. Matsushita, D. Steppenbeck

Theory Collaboration:

Univ. of Surrey
J. A. Tostevin, E.C. Simpson

NSCL/ MSU B.A. Brown

TRIUMF P. Navratil