

Quasi-free One-proton Knockout Reactions along the Oxygen Isotopic Chain

Leyla Atar^{1,2}

T. Aumann^{1,2}, C. Bertulani³, S. Paschalis¹

for R³B Collaboration

1. TU Darmstadt

2. GSI, Darmstadt

3. Texas A&M University-Commerce, USA

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Outline

- Introduction
- Experimental Setup
- Data Analysis
- Experimental Results
- Summary & Outlook

Single-Particle Strength

IPM: Nucleons are single particles moving independently in a mean field created by all nucleons.

- Reduction factor

$$R = \sigma_{\text{exp}} / \sigma_{\text{IPM}}$$

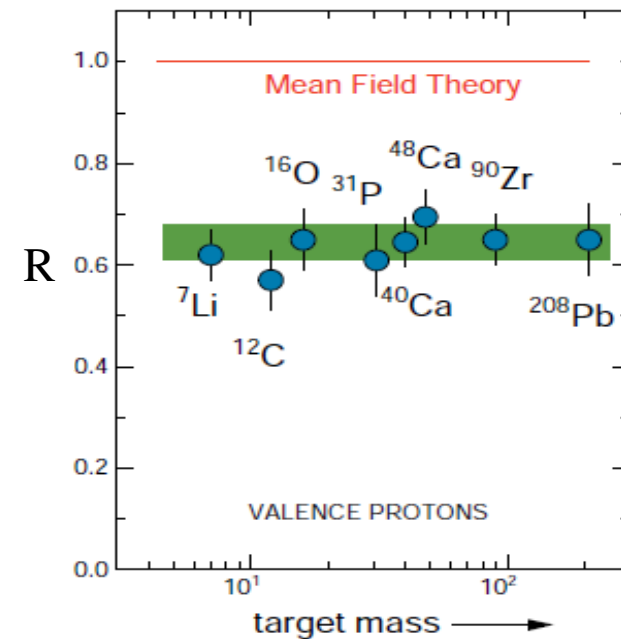
relative to the IPM!

- 30-40% deviation of the single-particle strength relative to the IPM

- Correlations:
not included in the IPM
such as short-range and tensor,
long-range

- configuration mixing
- high momenta

(e,e'p) reactions at NIKHEF



H. Dickhoff, C. Barbieri Prog. Nucl. Phys. 52, 377 (2004)

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

- NIKHEF data is limited to stable nuclei and valence proton states.

Quenching of Single-Particle Strength

- Latest compilation including exotic nuclei from (e,e'p), proton and neutron removal reactions

- Isospin dependency of single-particle strength in asymmetric systems?

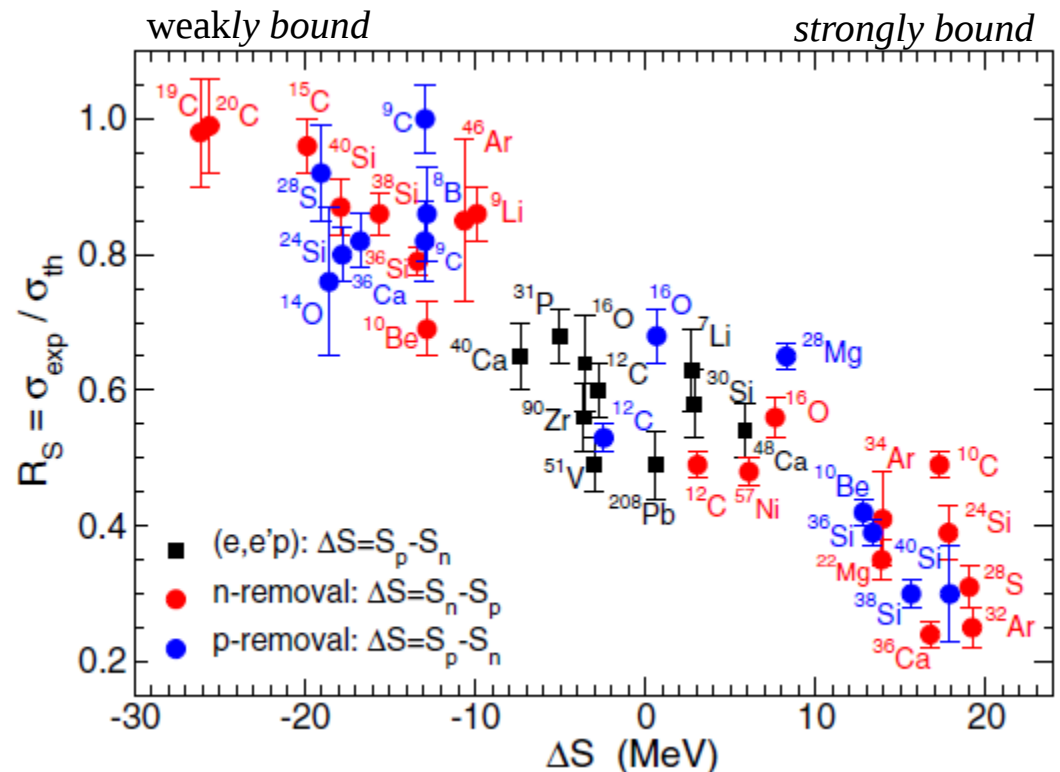
Quenching of single-particle strength in strongly bound states?

→ origin unclear

- Nucleon removal reactions with exotic beams at intermediate energies are limited to surface localized reactions

- Reaction mechanism?
- Missing correlations in SM?

One-nucleon knockout reactions at intermediate energies



Reduction factor **relative to a certain Shell Model:**

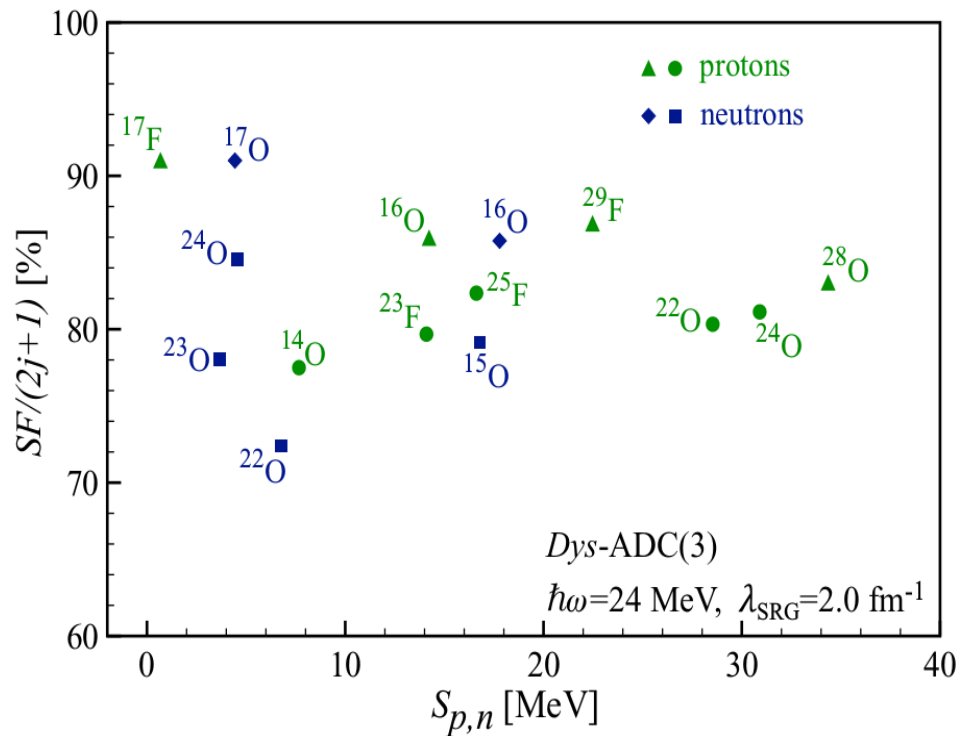
$$R_s = \sigma_{\text{exp}} / \sigma_{\text{SM}}$$

correlations are partially included!

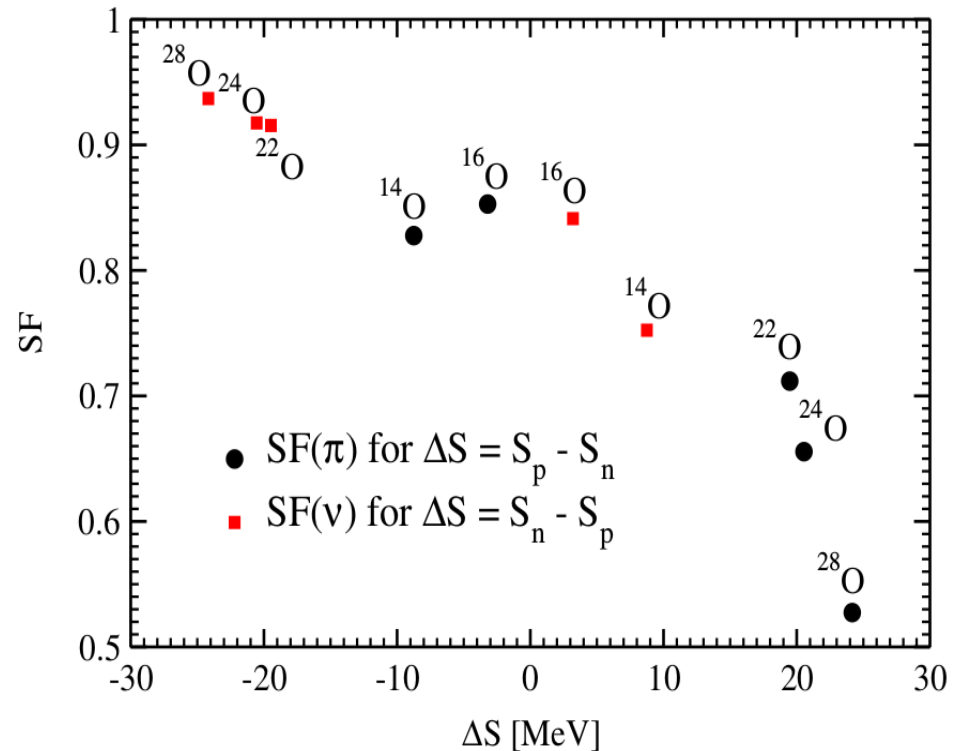
Ab-initio Theory: Weak Dependence

- SCGF with chiral 3N interactions at N3LO
- weak ΔS dependence from 0.7 to 0.9

- Coupled-cluster calculations with N2LO NN
- weak ΔS dependence with further decrease at the dripline due to coupling to continuum



Cipollene et al. Phys. Rev. C 92, 014306 (2015)



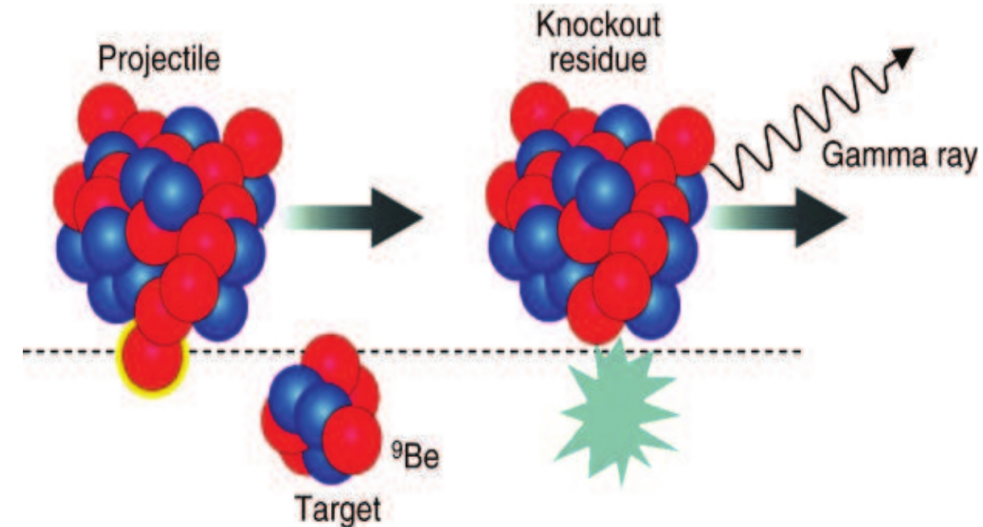
Jensen et al. Phys. Rev. Lett. 107, 032501 (2011)



Disagreement with knockout experiments at intermediate energies analyzed with eikonal theory!

Knockout Reactions at Intermediate Energies

- on light nuclear targets (e.g. Be, C)
- Intermediate beam energy $\sim 100\text{MeV/u}$
- nucleon from projectile scattered
- eikonal & sudden approximations
- strong absorption $\rightarrow$ surface localized



A. Gade et al. PNP 60(1):161-224,2008

Measurements

- cross section $\rightarrow$ reduction/spectroscopic factor
- Momentum distribution $\rightarrow$ angular momentum ℓ
- γ -ray spectroscopy $\rightarrow$ selection of final channel

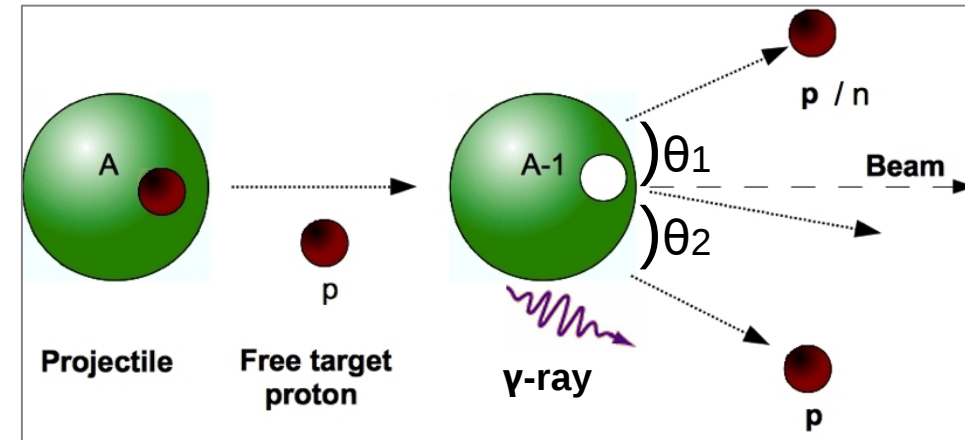
Deduced quantities

$$\mathbf{P}_{A-1} = -\mathbf{P}_{p/n}$$

residue momentum $\rightarrow$ angular momentum ℓ of removed nucleon

Complementary Approach: Quasi-free Scattering at High Energies

- proton target → quasi-free NN reaction and more sensitivity to deeply bound states
- Relativistic energies (0.2-1 GeV/u)
 - **sudden approximation**: fast reaction (10^{-23} s) and spectator core
 - weaker absorption in nucleus
 - free NN cross section is min (~ 300 MeV)
- **eikonal approximation**
 - momentum of residue corresponds to momentum of knocked nucleon
- projectile and target nucleon scattered

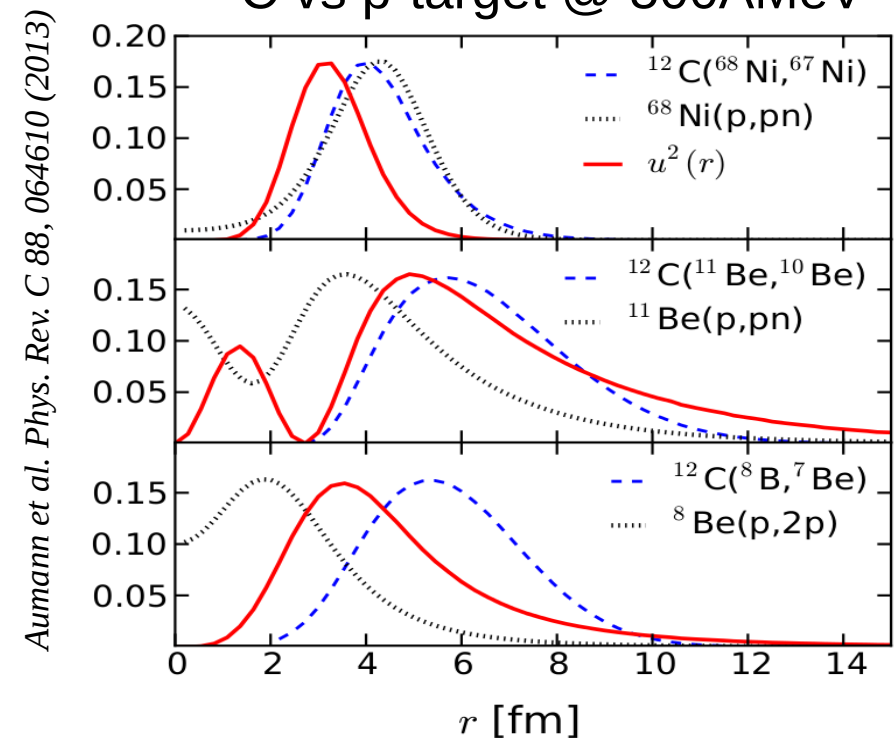


$$\mathbf{P}_{A-1} = -\mathbf{P}_{p/n}$$

residue momentum → angular momentum ℓ of removed nucleon

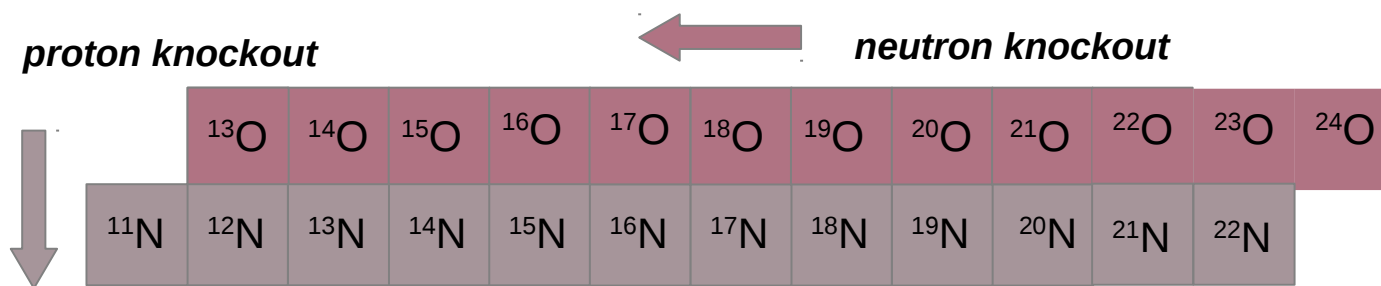
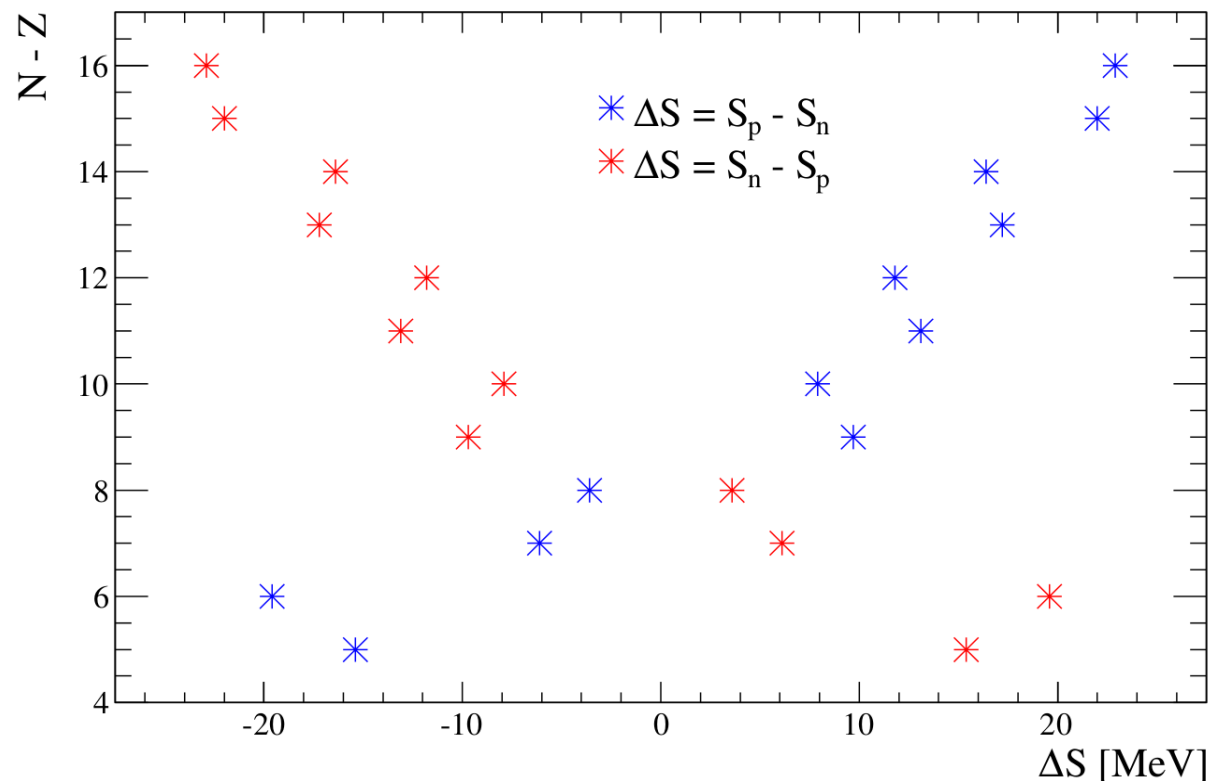
cross section → R/C^2S
 momentum → ℓ
 γ -ray → final channel

Nucleon removal probability
 ^{12}C vs p-target @ 500A MeV



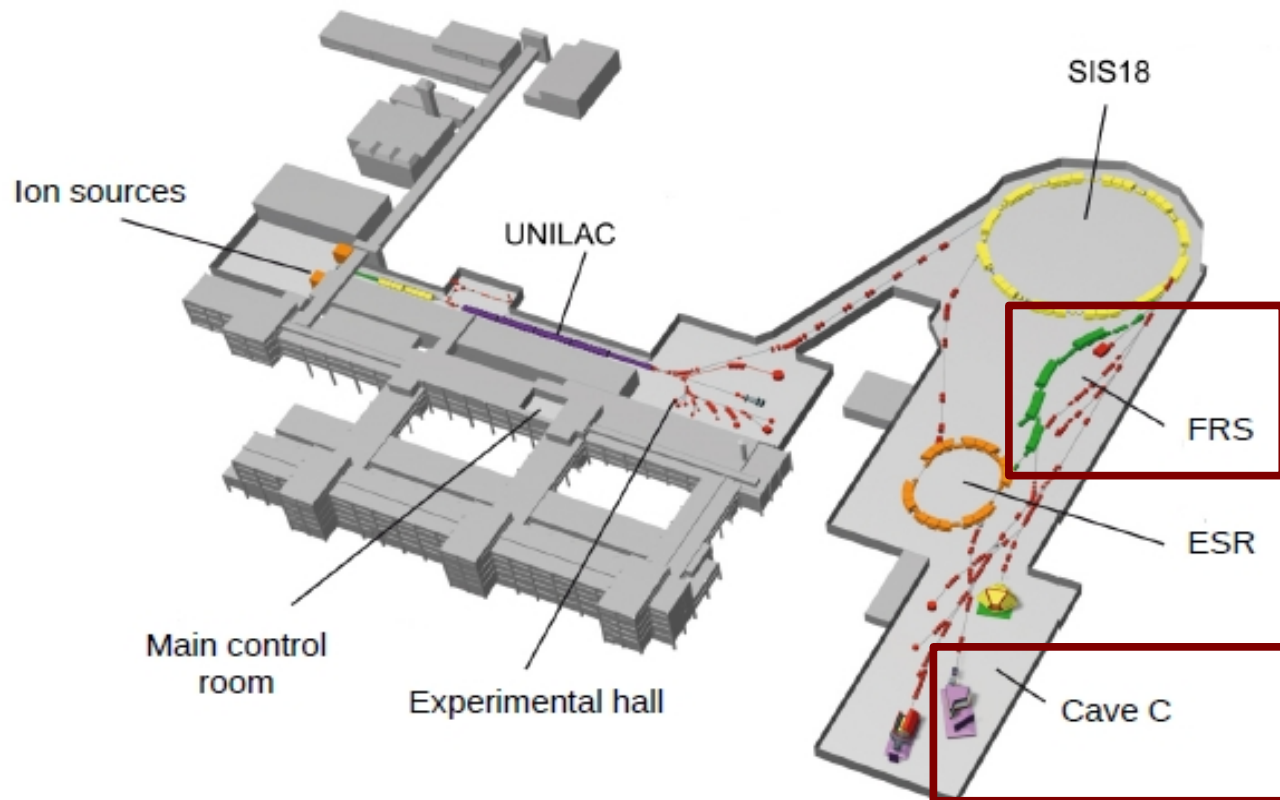
Oxygen Isotopic Chain

- Changing of single-particle strength with proton-neutron asymmetry
- Oxygen isotopic chain offers a large variation in isospin
- Systematic study of Oxygen isotopes via (p,pn) & (p,2p) reactions

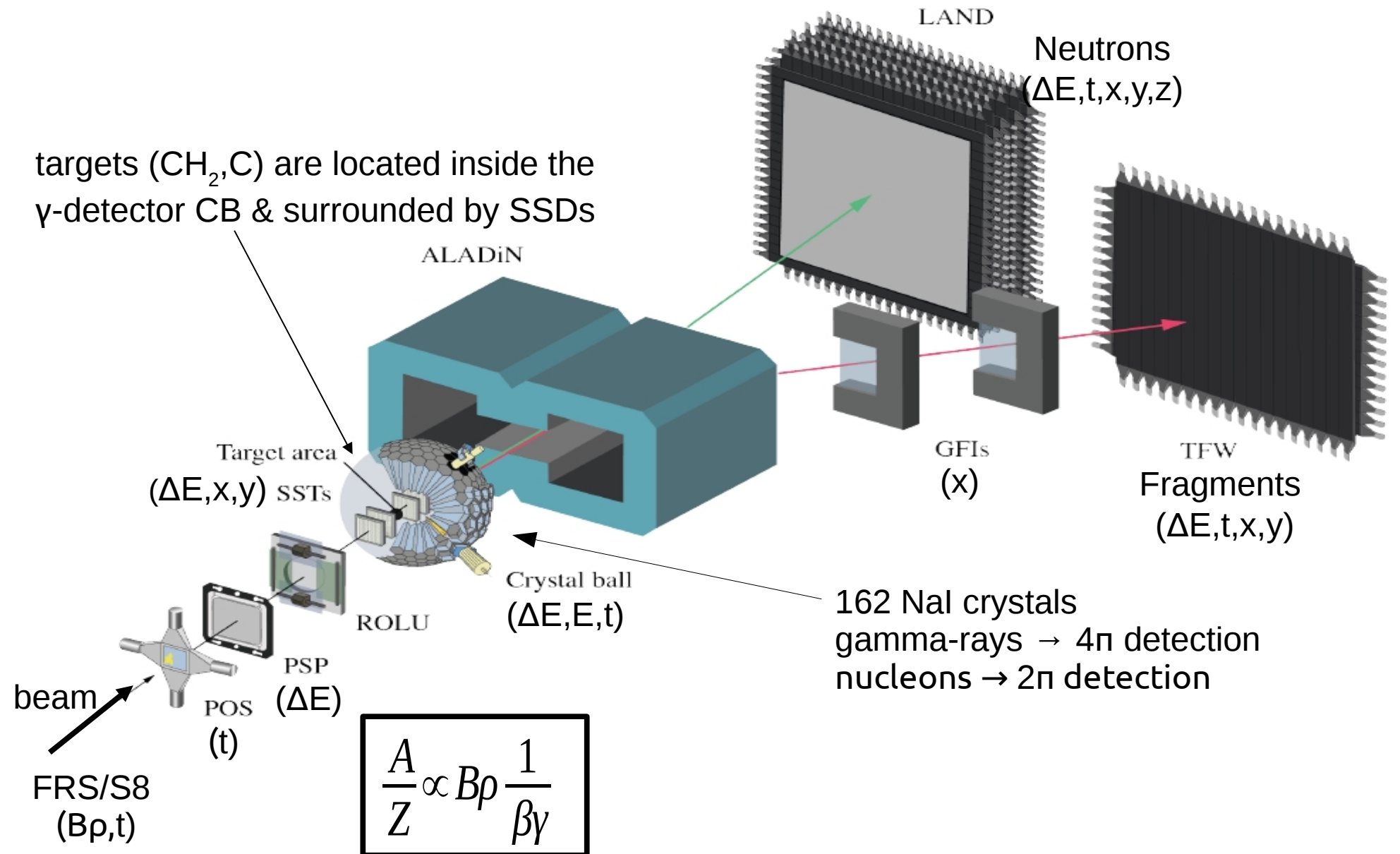


GSI Accelerator Facility

- Fragmentation of primary 490 AMeV ^{40}Ar beam on ^9Be target ($3 \cdot 10^{10}$ ion/spill)
- Selection of radioactive beam at Fragment Separator (FRS) by in-flight method
- Secondary beam $^{13-24}\text{O}$ delivered to Cave C

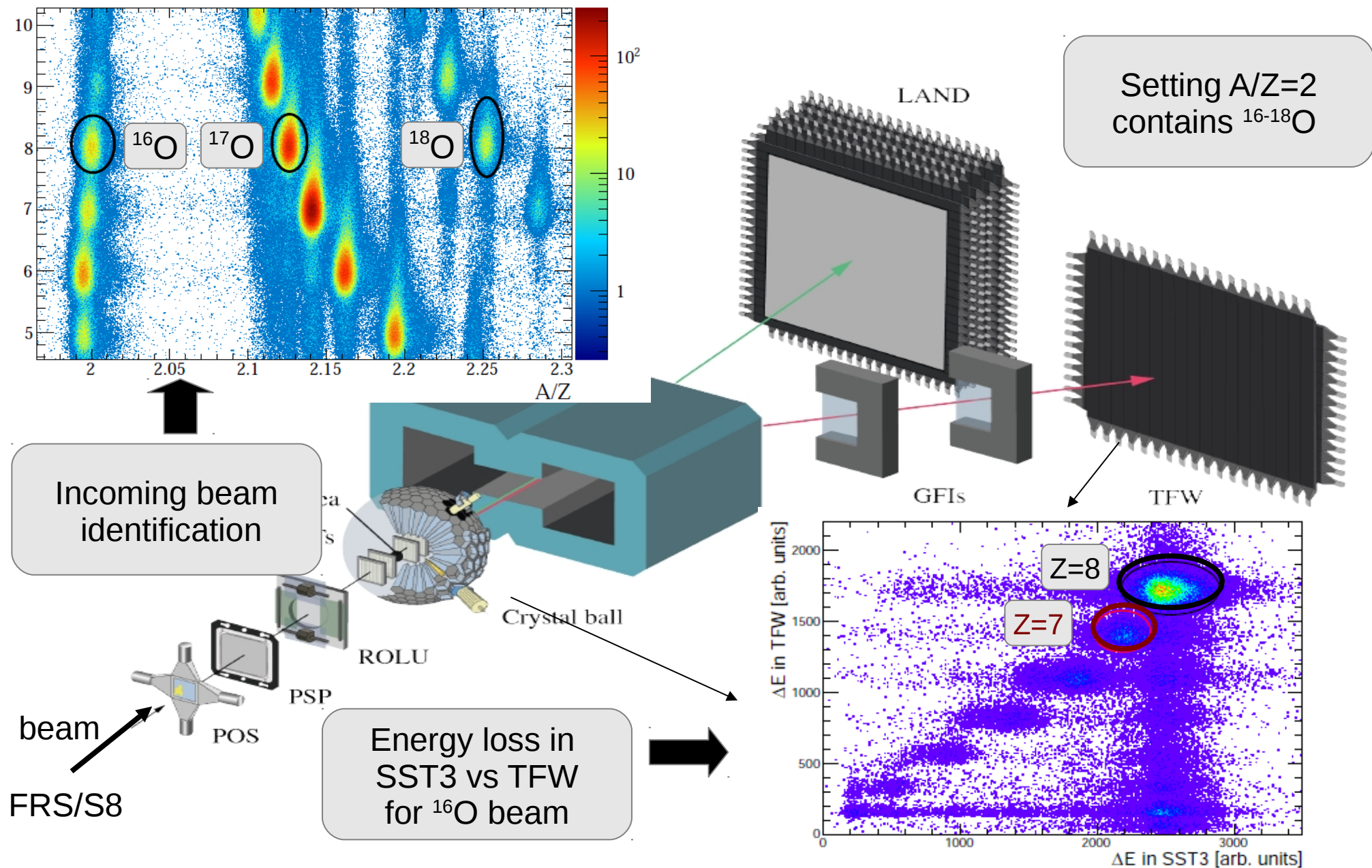


S393 Experiment at R³B/LAND Setup @ GSI

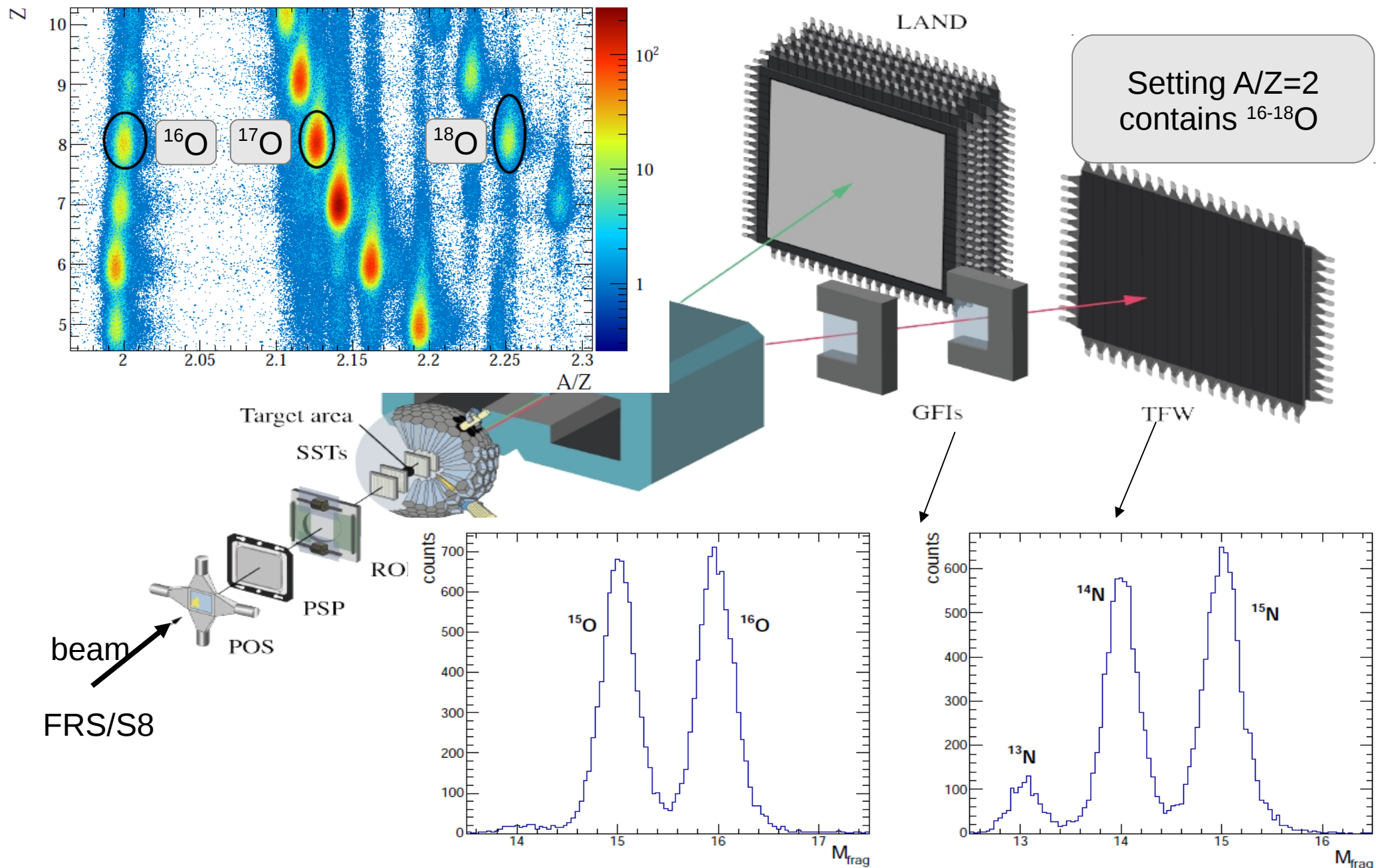


Picture taken from S. Altstadt

Incoming Beam & Outgoing Fragment Identification

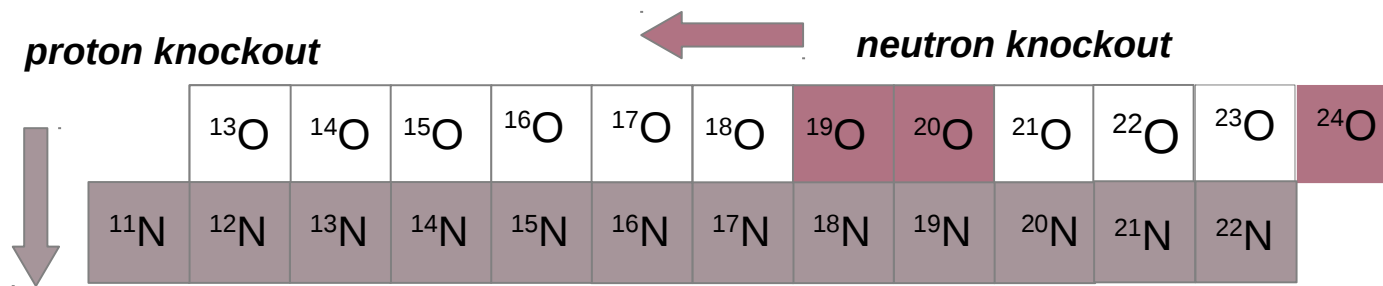


Incoming Beam & Outgoing Fragment Identification

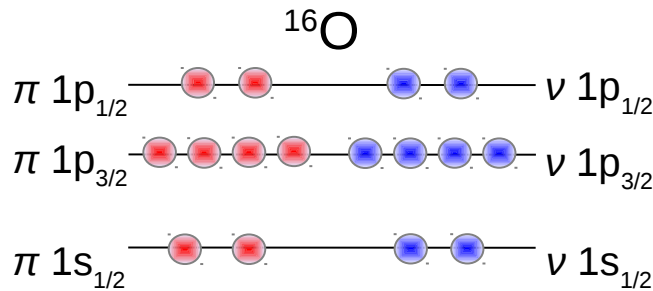


Experimental Results

- selection of quasi-free reaction channel: two outgoing nucleon + bound residue
- reactions on proton : subtracting of carbon induced reactions from CH_2 reactions
- ground state configuration of projectile according to IPM
- inclusive cross section restricted to bound core states



Inclusive Cross Section & Transverse Momentum: $^{16}\text{O}(p,2p)^{15}\text{N}$



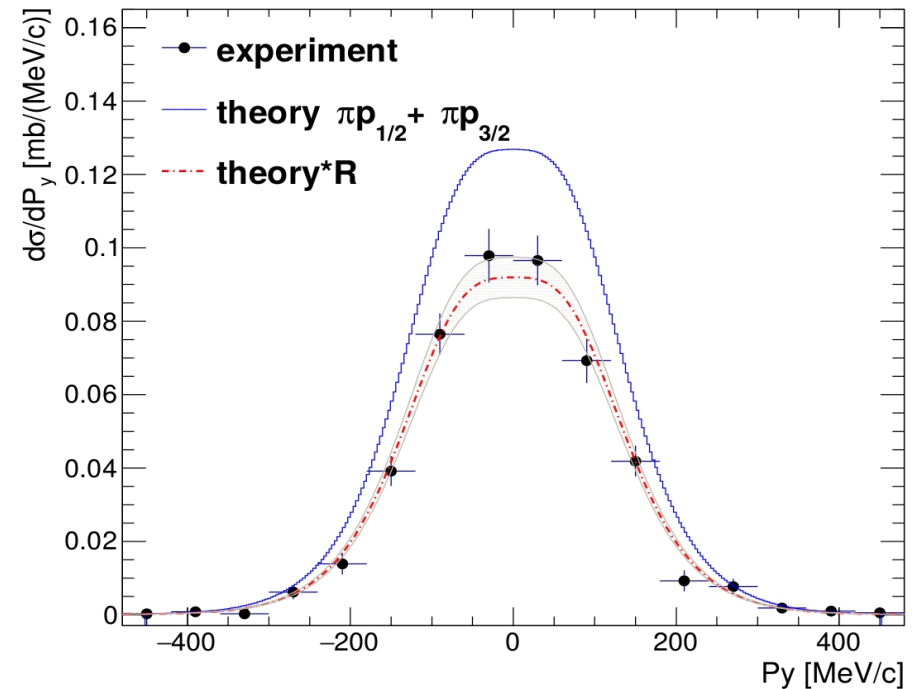
- Reaction theory: C. Bertulani, eikonal theory
T. Aumann, C. Bertulani, J. Ryckebusch Phys. Rev. C88, 064610 (2013)
- Multiple scattering $\rightarrow$ Glauber model
- Absorption $\rightarrow$ complex optical potential

$\sigma_{\text{exp}} [\text{mb}]$	28(1)
$\sigma_{\text{theo}}(1p_{1/2})$	13
$\sigma_{\text{theo}}(1p_{3/2})$	25
R	0.73(3)
$S_{p/n} [\text{MeV}]$	12/16

Reduction factor
 $R = \sigma_{\text{exp}} / \sigma_{\text{theo}}$

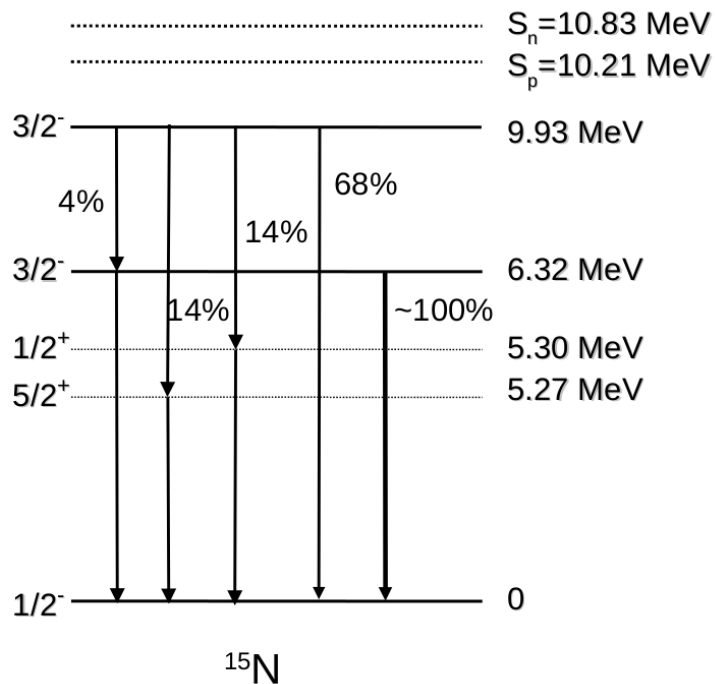
$R = 0.65(5)$
from
(e,e'p) @ NIKHEF
 $\rightarrow$ agreement!

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



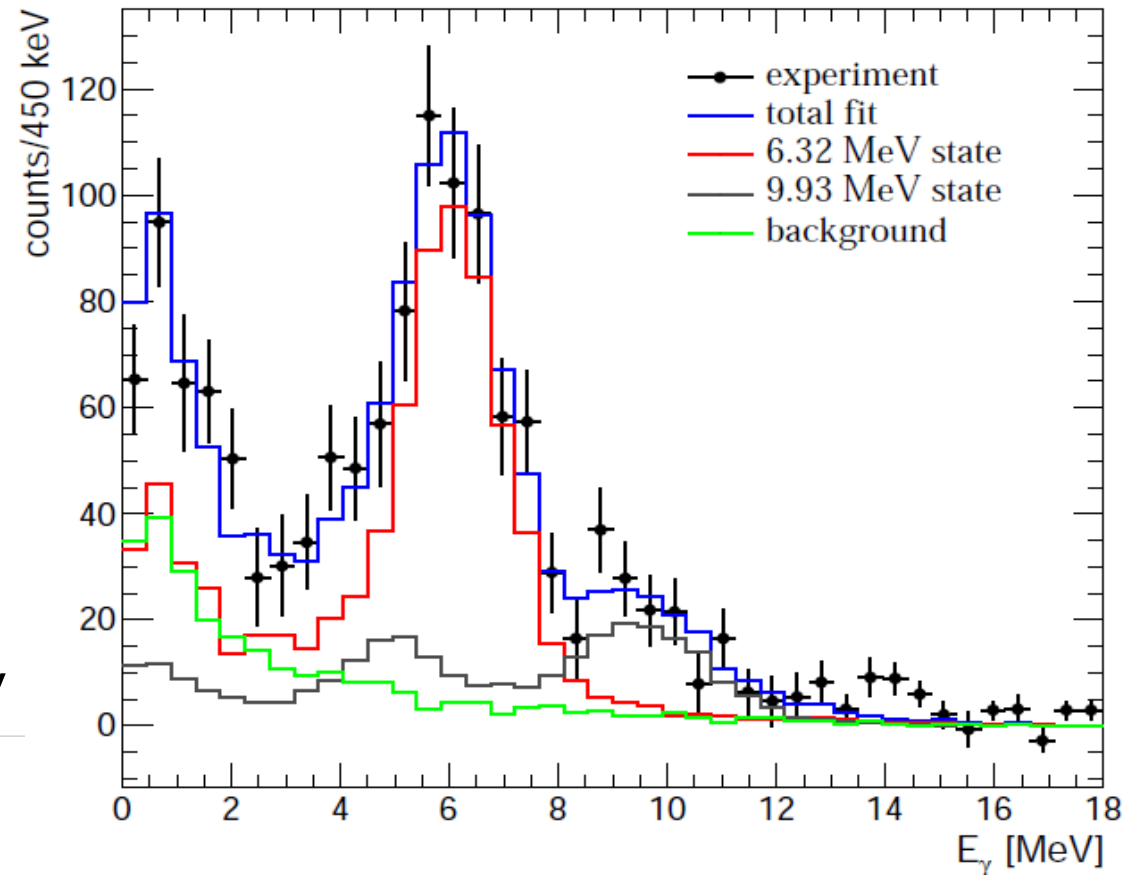
Inclusive P_y distribution for
 $1p_{1/2}$ and $1p_{3/2}$ proton knockout

Partial Cross Sections and Spectroscopic Factors: $^{16}\text{O}(p,2p)^{15}\text{N}$



J^π	$1/2^-$ 0.0 MeV	$3/2^-$ 6.3 MeV	$3/2^-$ 9.9 MeV
b (%)	36(5)	47(4)	17(3)
σ_{exp} [mb]	10(2)	13(1)	5(1)
C^2S	1.5(3)	2.1(2)	0.7(1)
C^2S (e,e'p)	1.3(1)	2.4(2)	0.1(2)

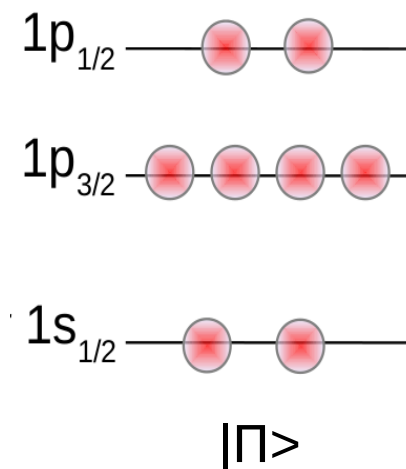
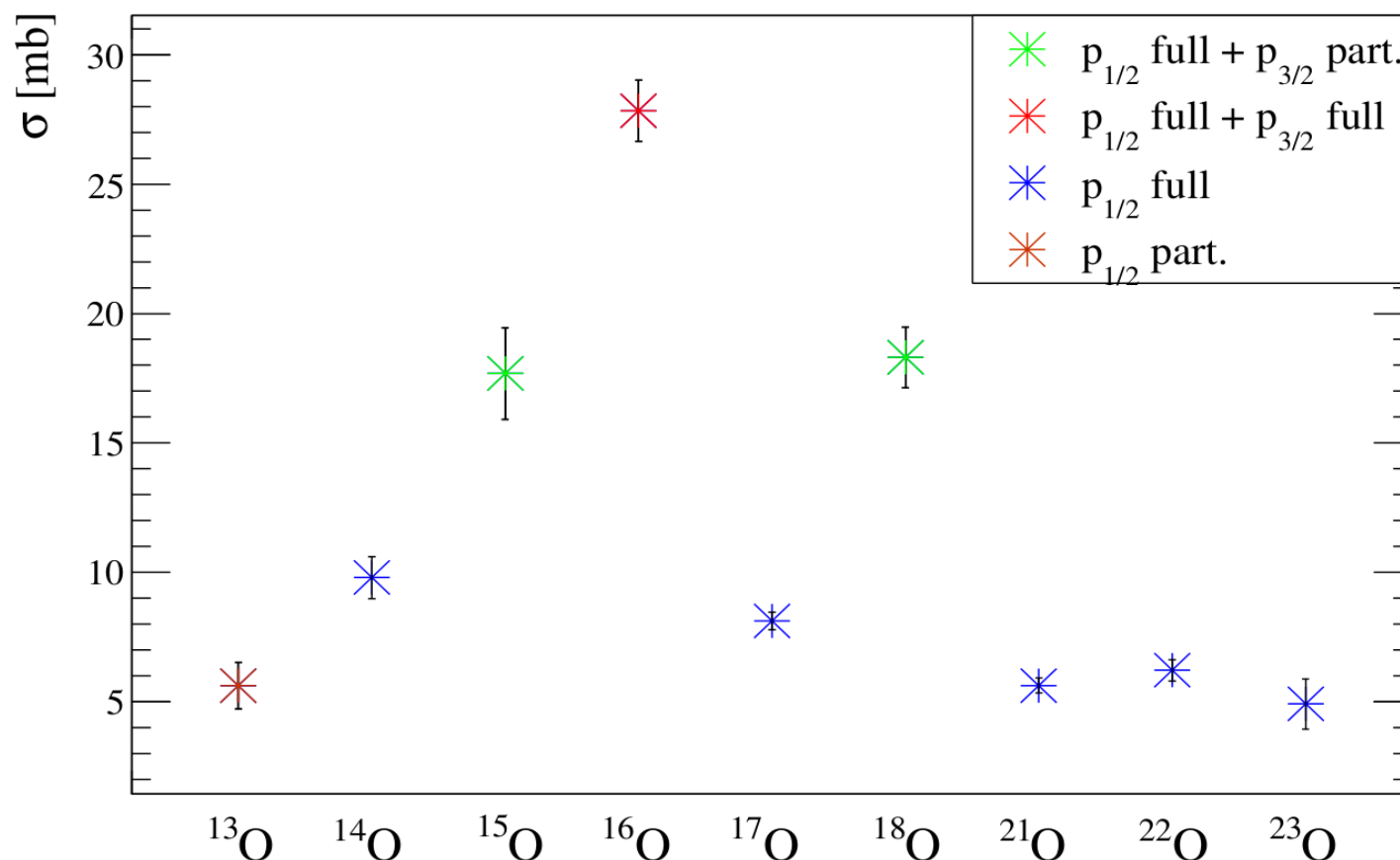
Doppler corrected γ -spectrum measured in coincidence with $^{16}\text{O}(p,2p)^{15}\text{N}$



Spectroscopic factors deduced from the theoretical predictions and partial cross sections obtained from the fit of the γ -spectrum.

← (e,e'p) @ NIKHEF

Inclusive Cross Sections for Projectiles $^{13-18}\text{O}$ and $^{21-23}\text{O}$

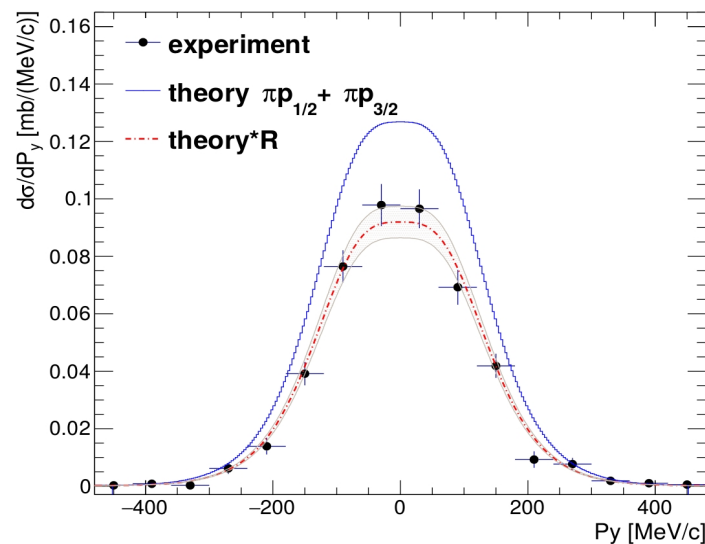


(p,2p) reaction channel

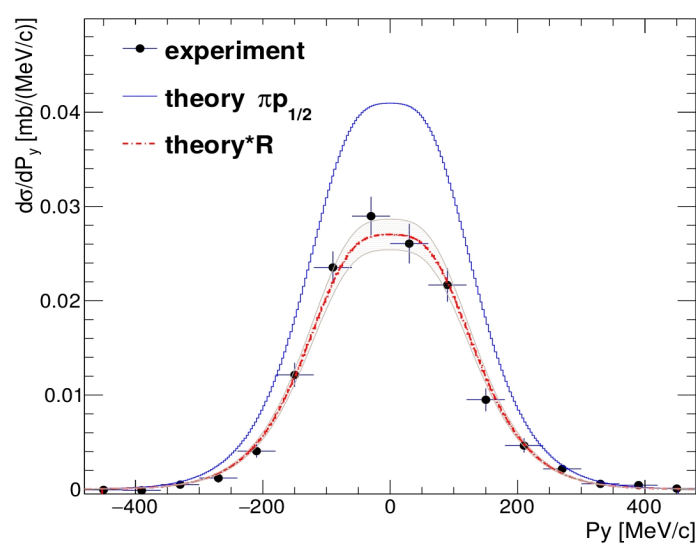
- $^{15-16}\text{O}$ and $^{18}\text{O} \rightarrow$ larger $S_n \rightarrow$ knockout of $1p_{1/2}$ and $1p_{3/2}$ protons
- $^{13-14-17}\text{O}$ and $^{21-23}\text{O} \rightarrow$ lower $S_{n/p} \rightarrow$ knockout of only $1p_{1/2}$ protons
- fragmentation of $1p_{3/2}$ proton strengths!

y-Projection of Transverse Momentum Distributions

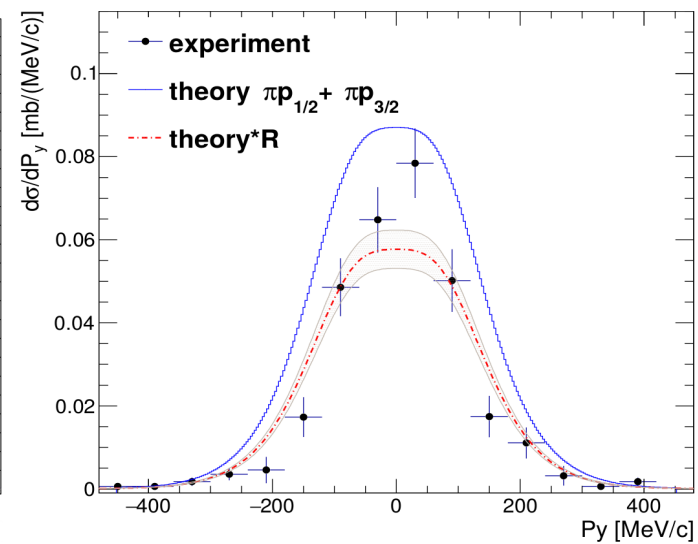
$^{16}\text{O}(p,2p)^{15}\text{N}$



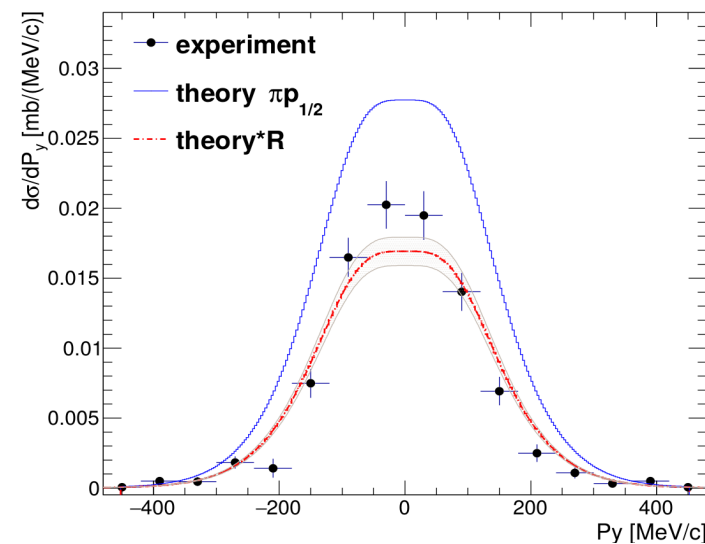
$^{17}\text{O}(p,2p)^{16}\text{N}$



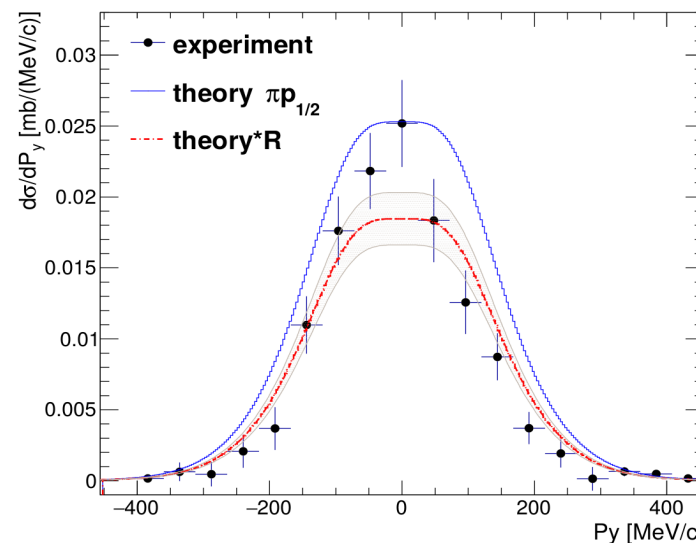
$^{18}\text{O}(p,2p)^{17}\text{N}$



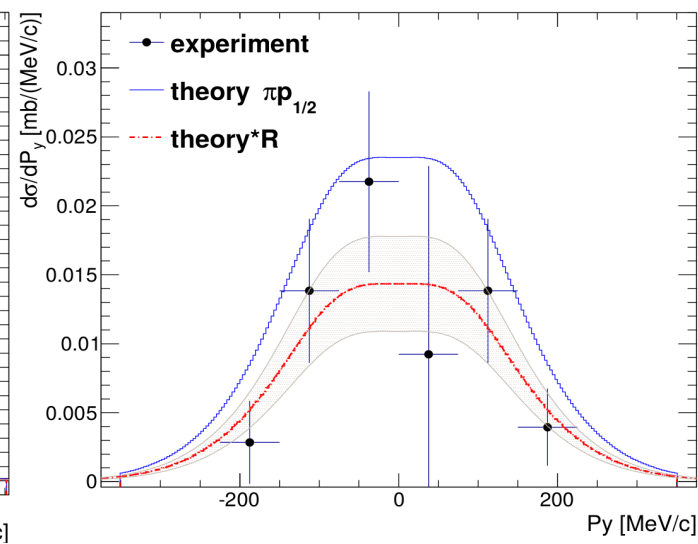
$^{21}\text{O}(p,2p)^{20}\text{N}$



$^{22}\text{O}(p,2p)^{21}\text{N}$



$^{23}\text{O}(p,2p)^{22}\text{N}$

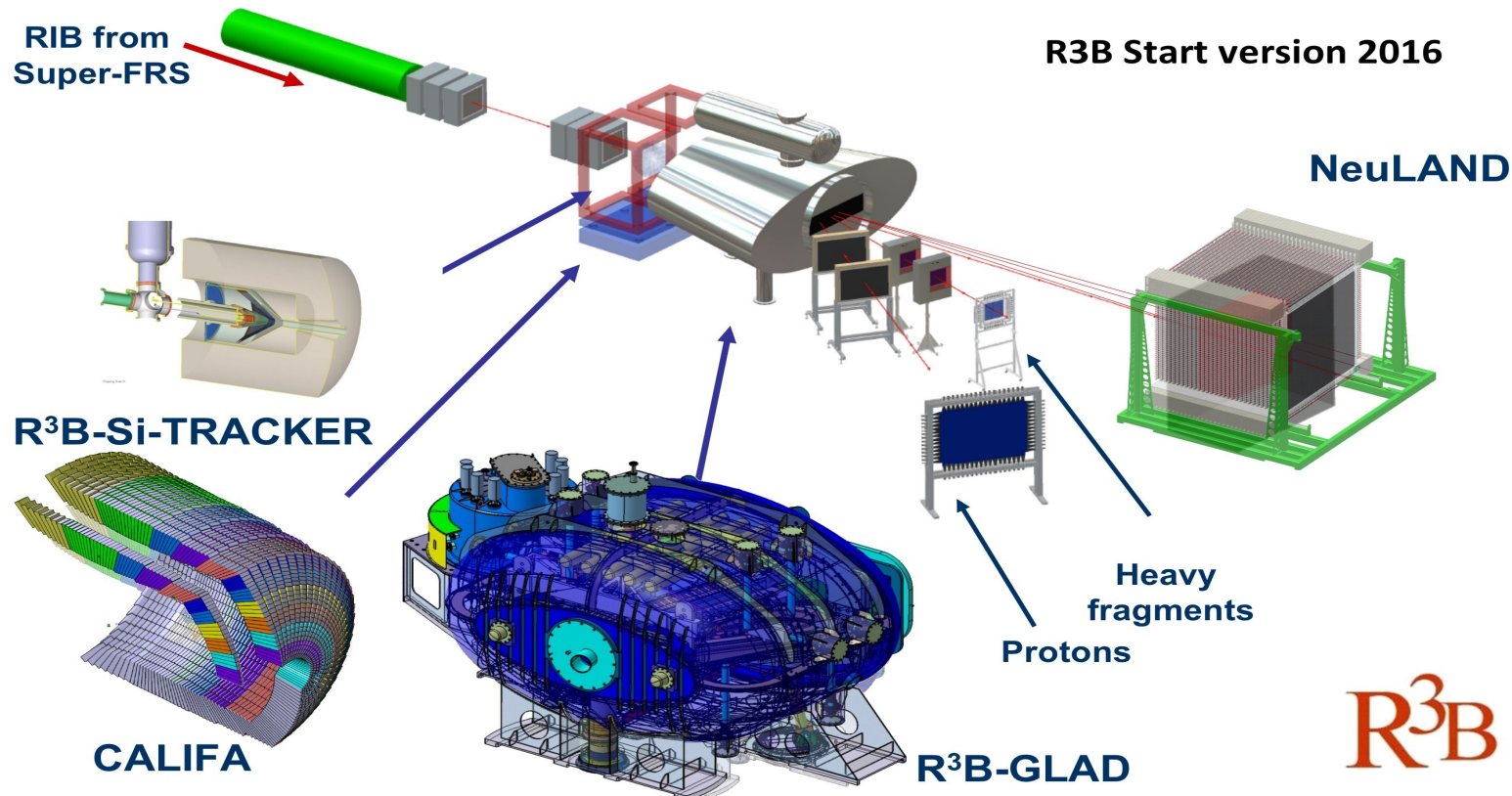


Summary

- Quasi-free knockout reactions in inverse kinematics provide a direct tool to obtain spectroscopic information.
- The results for the projectiles $^{13-18}\text{O}$ and $^{21-23}\text{O}$ have been obtained.
- The reduction factor obtained from $^{16}\text{O}(\text{p},2\text{p})^{15}\text{N}$ reaction is in agreement with the results from $(\text{e},\text{e}'\text{p})$ reaction at NIKHEF facility.
- It is necessary to understand reaction mechanism for knockout of deeply bound states at intermediate energies.

Outlook

- Systematic analysis for entire Oxygen isotopic chain
- Similar analysis for the (p,pn) channel
- Development of optimized detector system for the future R³B (Reactions with Relativistic Radioactive Beams) program at FAIR.



R³B

*Thanks
for your attention*

The R³B Collaboration

Aksouh, Farouk; Al-Khalili, Jim; Algora, Alejandro; Alkhasov, Georgij; Altstadt, Sebastian; Alvarez, Hector; Atar, Leyla; Audouin, Laurent; Aumann, Thomas; Pellereau, Eric; Martin, Julie-Fiona; Gorbinet, Thomas; Seddon, Dave; Kogimtzis, Mos; Avdeichikov, Vladimir; Barton, Charles; Bayram, Murat; Belier, Gilbert; Bemmerer, Daniel; Michael Bendel; Benlliure, Jose; Bertulani, Carlos; Bhattacharya, Sudeb; Bhattacharya, Chandana; Le Bleis, Tudi; Boilley, David; Boretzky, Konstanze; Borge, Maria Jose; Botvina, Alexander; Boudard, Alain; Boutoux, Guillaume; Boehmer, Michael; Caesar, Christoph; Calvino, Francisco; Casarejos, Enrique; Catford, Wilton; Cederkall, Joakim; Cederwall, Bo; Chapman, Robert; Alexandre Charpy; Chartier, Marielle; Chatillon, Audrey; Chen, Ruofu; Christophe, Mayri; Chulkov, Leonid; Coleman-Smith, Patrick; Cortina, Dolores; Crespo, Raquel; Csatlos, Margit; Cullen, David; Czech, Bronislaw; Danilin, Boris; Davinson, Tom; Paloma Diaz; Dillmann, Iris; Fernandez Dominguez, Beatriz; Ducret, Jean-Eric; Duran, Ignacio; Egelhof, Peter; Elekes, Zoltan; Emling, Hans; Enders, Joachim; Eremin, Vladimir; Ershov, Sergey N.; Ershova, Olga; Eronen, Simo; Estrade, Alfredo; Faestermann, Thomas; Fedorov, Dmitri; Feldmeier, Hans; Le Fevre, Arnaud; Fomichev, Andrey; Forssen, Christian; Freeman, Sean; Freer, Martin; Friese, Juergen; Fynbo, Hans; Gacsi, Zoltan; Garrido, Eduardo; Gasparic, Igor; Gastineau, Bernard; Geissel, Hans; Gelletly, William; Genolini, B.; Gerl, Juergen; Gernhaeuser, Roman; Golovkov, Mikhail; Golubev, Pavel; Grant, Alan; Grigorenko, Leonid; Grosse, Eckart; Gulyas, Janos; Goebel, Kathrin; Gorska, Magdalena; Haas, Oliver Sebastian; Haiduc, Maria; Hasegan, Dumitru; Heftrich, Tanja; Heil, Michael; Heine, Marcel; Heinz, Andreas; Ana Henriques; Hoffmann, Jan; Holl, Matthias; Hunyadi, Matyas; Ignatov, Alexander; Ignatyuk, Anatoly V.; Ilie, Cherciu Madalin; Isaak, Johann; Isaksson, Lennart; Jakobsson, Bo; Jensen, Aksel; Johansen, Jacob; Johansson, Hakan; Johnson, Ron; Jonson, Bjoern; Junghans, Arnd; Jurado, Beatriz; Jaehrling, Simon; Kailas, S.; Kalantar, Nasser; Kalliopuska, Juha; Kanungo, Rituparna; Kelic-Heil, Aleksandra; Kezzar, Khalid; Khanzadeev, Alexei; Kissel, Robert; Kisselev, Oleg; Klimkiewicz, Adam; Kmiecik, Maria; Koerper, Daniel; Kojouharov, Ivan; Korshennikov, Alexei; Korten, Wolfram; Krasznahorkay, Attila; Kratz, Jens Volker; Kresan, Dima; Anatoli Krivchitch; Kroell, Thorsten; Krupko, Sergey; Kruecken, Reiner; Kulesa, Reinhard; Kurz, Nikolaus; Kuzmin, Eugenii; Labiche, Marc; Langanke, Karl-Heinz; Langer, Christoph; Lapoux, Valerie; Larsson, Kristian; Laurent, Benoit; Lazarus, Ian; Le, Xuan Chung; Leifels, Yvonne; Lemmon, Roy; Lenske, Horst; Lepine-Szily, Alinka; Leray, Sylvie; Letts, Simon; Li, Songlin; Liang, Xiaoying; Lindberg, Simon; Lindsay, Scott; Litvinov, Yuri; Lukasik, Jerzy; Loeher, Bastian; Mahata, Kripamay; Maj, Adam; Marganec, Justyna; Meister, Mikael; Mittag, Wolfgang; Movsesyan, Alina; Mutterer, Manfred; Muentz, Christian; Nacher, Enrique; Najafi, Ali; Nakamura, Takashi; Neff, Thomas; Nilsson, Thomas; Nociforo, Chiara; Nolan, Paul; Nolen, Jerry; Nyman, Goran; Obertelli, Alexandre; Obradors, Diego; Ogloblin, Aleksey; Oi, Makito; Palit, Rudrajyoti; Panin, Valerii; Paradela, Carlos; Paschalis, Stefanos; Pawlowski, Piotr; Petri, Marina; Pietralla, Norbert; Pietras, Ben; Pietri, Stephane; Plag, Ralf; Podolyak, Zsolt; Pollacco, Emanuel; Potlog, Mihai; Datta Pramanik, Ushasi; Prasad, Rajeshwari; Fraile Prieto, Luis Mario; Pucknell, Vic; Galaviz -Redondo, Daniel; Regan, Patrick; Reifarh, Rene; Reinhardt, Tobias; Reiter, Peter; Rejmund, Fanny; Ricciardi, Maria Valentina; Richter, Achim; Rigollet, Catherine; Riisager, Karsten; Rodin, Alexander; Rossi, Dominic; Roussel-Chomaz, Patricia; Gonzalez Rozas, Yago; Rubio, Berta; Roeder, Marko; Saito, Takehiko; Salsac, Marie-Delphine; Rodriguez Sanchez, Jose Luis; Santosh, Chakraborty; Savajols, Herve; Savran, Deniz; Scheit, Heiko; Schindler, Fabia; Schmidt, Karl-Heinz; Schmitt, Christelle; Schnorrenberger, Linda; Schrieder, Gerhard; Schrock, Philipp; Sharma, Manoj Kumar; Sherrill, Bradley; Shrivastava, Aradhana; Shulgina, Natalia; Sidorchuk, Sergey; Silva, Joel; Simenel, Cedric; Simon, Haik; Simpson, John; Singh, Pushpendra Pal; Sonnabend, Kerstin; Spohr, Klaus; Stanoiu, Mihai; Stevenson, Paul; Strachan, Jon; Streicher, Brano; Stroth, Joachim; Syndikus, Ina; Suemmerer, Klaus; Taieb, Julien; Tain, Jose L.; Tanihata, Isao; Tashenov, Stanislav; Tassan-Got, Laurent; Tengblad, Olof; Teubig, Pamela; Thies, Ronja; Togano, Yasuhiro; Tostevin, Jeffrey A.; Trautmann, Wolfgang; Tuboltsev, Yuri; Turrior, Manuela; Typel, Stefan; Udias-Moinelo, Jose; Vaagen, Jan; Velho, Paulo; Verbitskaya, Elena; Veselsky, Martin; Wagner, Andreas; Walus, Wladyslaw; Wamers, Felix; Weick, Helmut; Wimmer, Christine; Winfield, John; Winkler, Martin; Woods, Phil; Xu, Hushan; Yakorev, Dmitry; Zegers, Remco; Zhang, Yu-Hu; Zhukov, Mikhail; Zieblinski, Mirosław; Zilges, Andreas;