Quasi-free one-nucleon Knockout Reactions on neutron-rich Oxygen Isotopes

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for R^{3}B Collaboration

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Outline

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

Single-Particle Strength

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

- Reduction factor

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

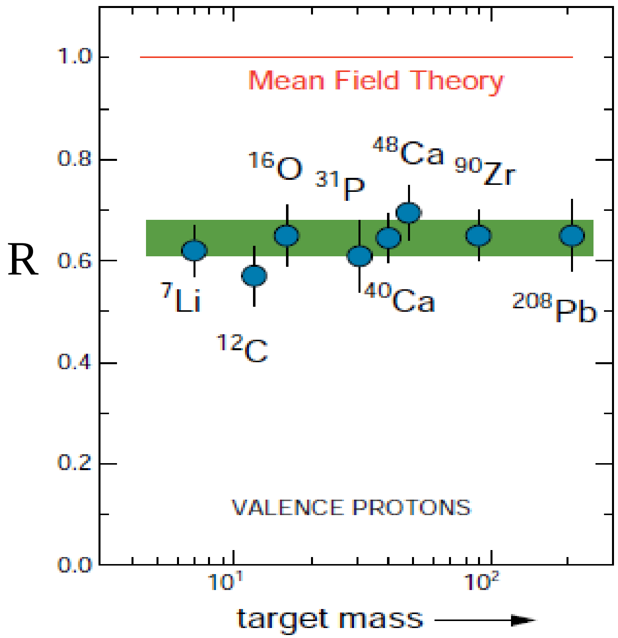
  relative to the IPM!

- 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

Quenching of Single-Particle Strength

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

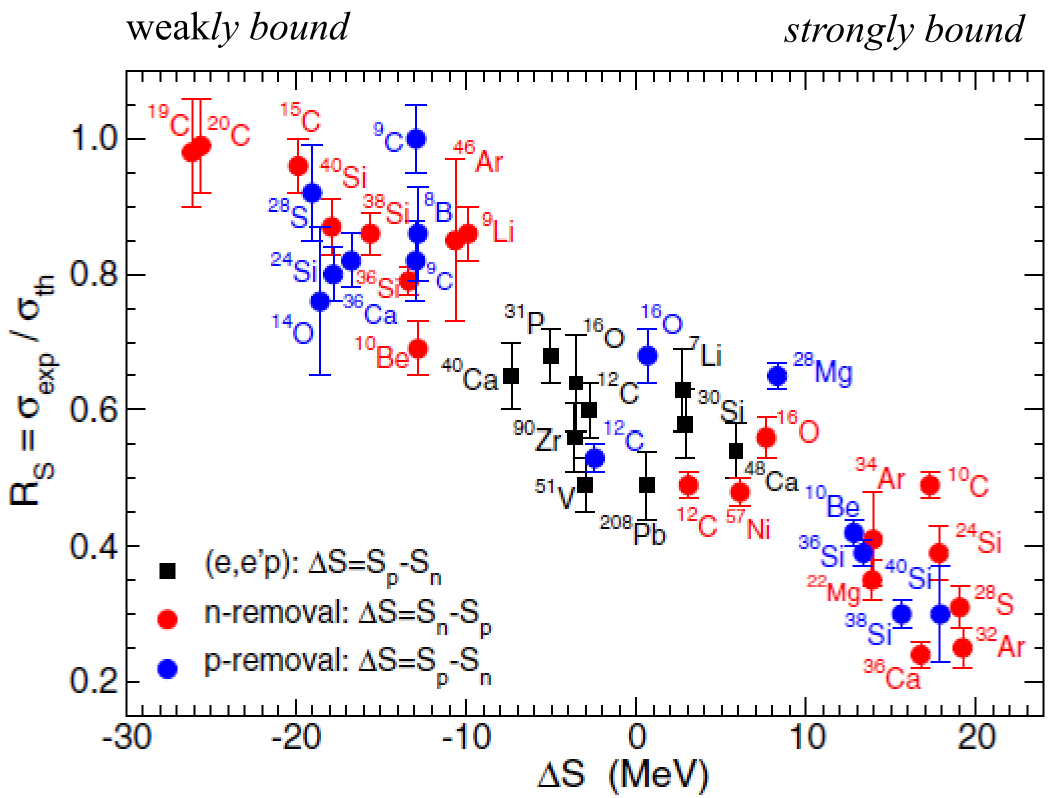
- Isospin dependency of single-particle strength in asymmetric systems?

  Quenching of single-particle strength in strongly bound states?

  → origin unclear

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

  → Reaction mechanism?



J.A.Tostevin, A. Gade Phys. Rev. C 90, 057602 (2014)

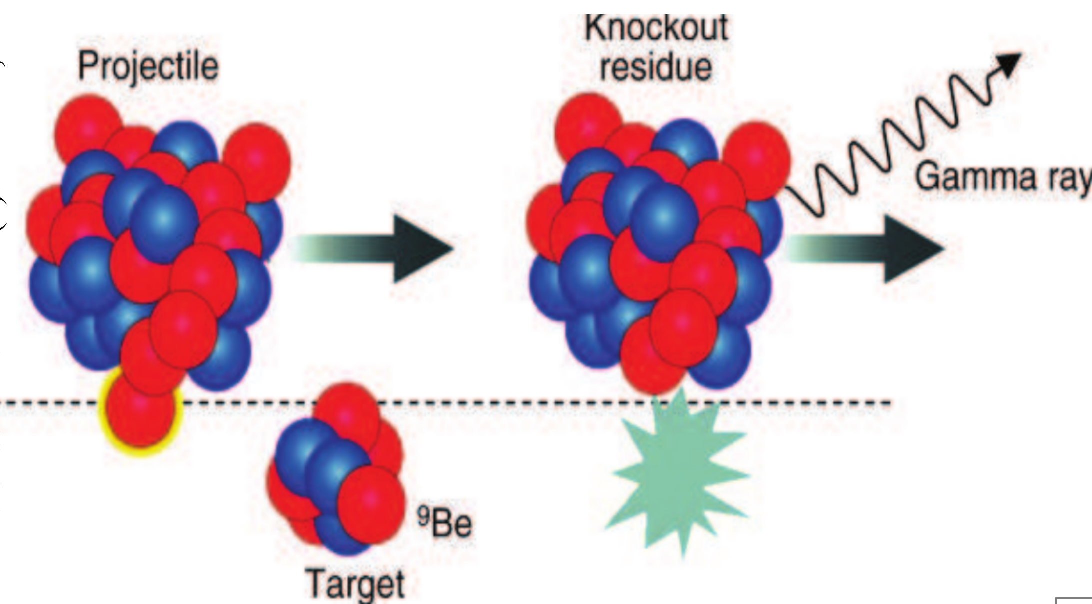
- Reduction factor relative to a certain Shell Model:

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

correlations are partially included!

Knockout Reactions vs Quasi-free Scattering

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

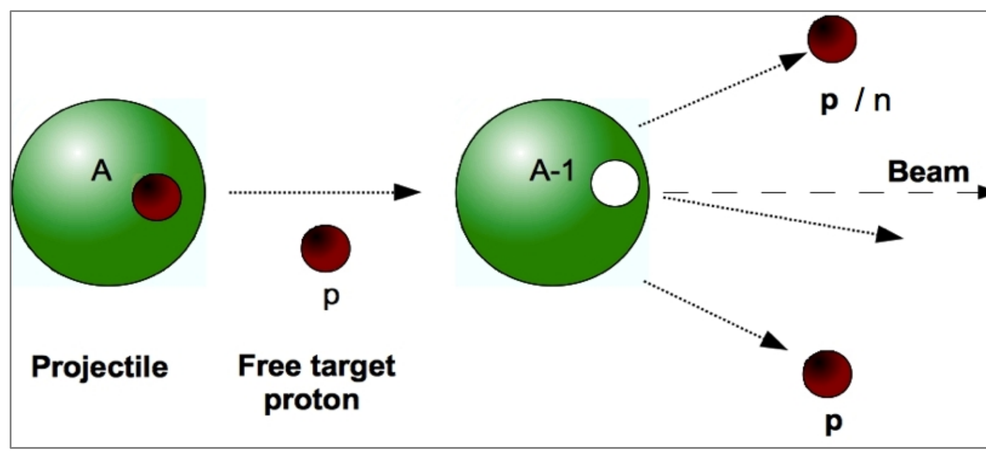


Knockout reactions:

- on light nuclear targets (e.g. Be, C)
- beam energy ~ 100MeV/u and higher
- strong absorption → surface localized

Quasi-free knockout reactions:

- proton target
  → quasi-free NN reactions
  → more sensitive to deeply bound states
- relativistic energies (0.2-1 GeV)
  → sudden approximation:
  fast reaction (10^{-23} s) and spectator core
  → minimizing final state interactions (σ_{NN} min ~300 MeV)

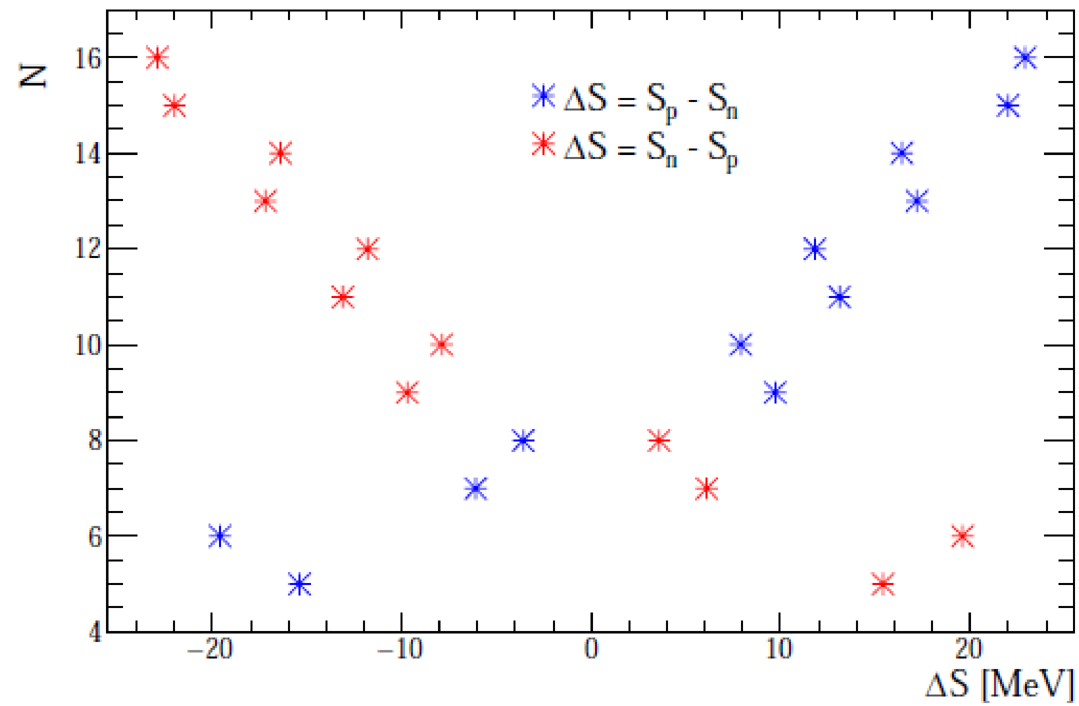


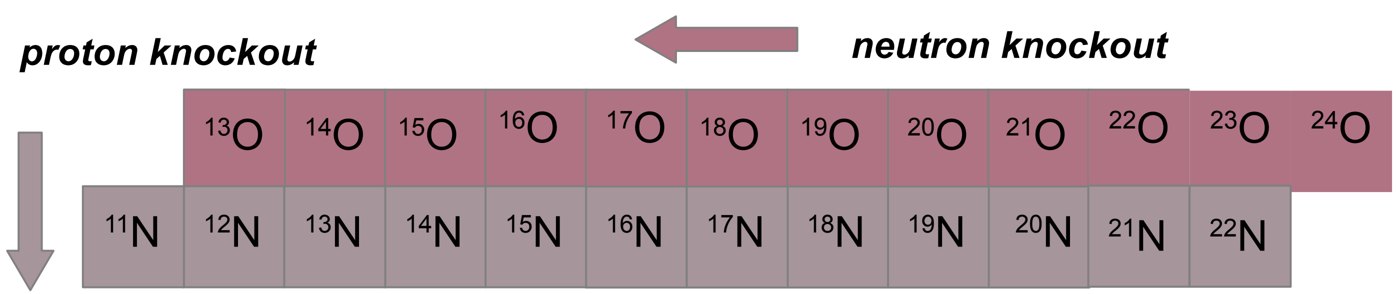
$$P_{A-1} = - P_{p/n}$$

residue momentum→ angular momentum of removed nucleon

Oxygen Isotopic Chain

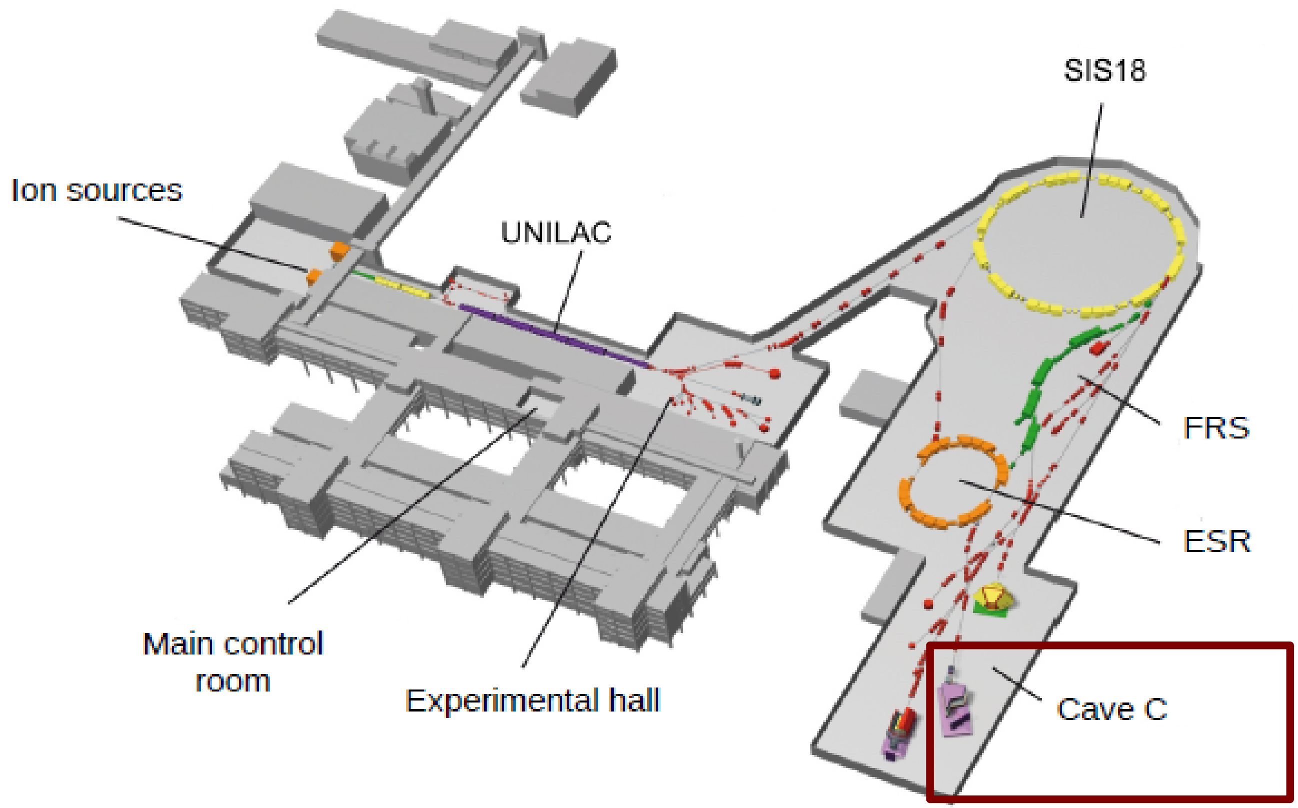
- Changing of single-particle strength with proton-neutron asymmetry
- Oxygen isotopic chain offers a large variation in isospin
- Systematic study of Oxygen isotopes via (p,pn) & (p,2p) reactions



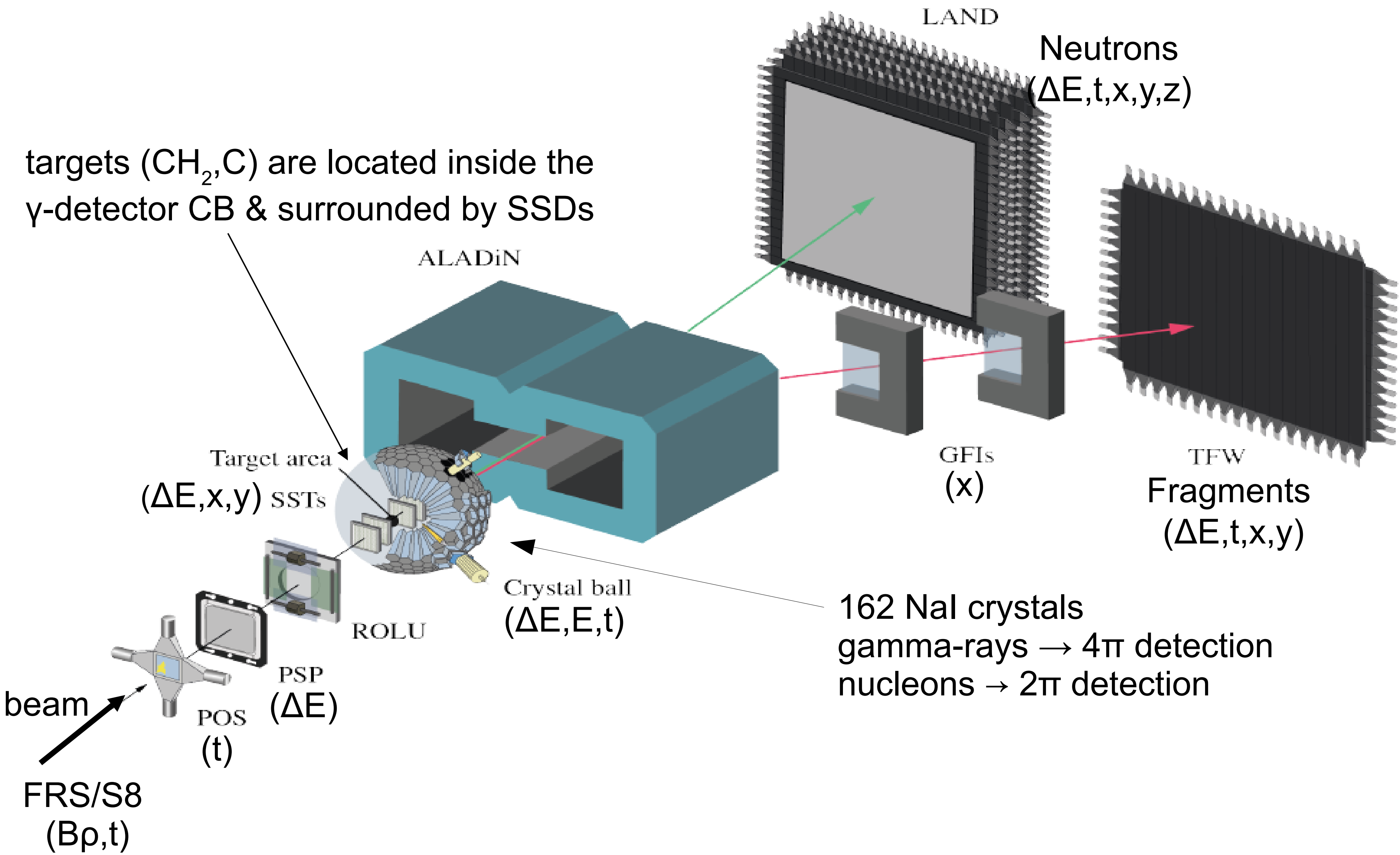


GSI Accelerator Facility

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

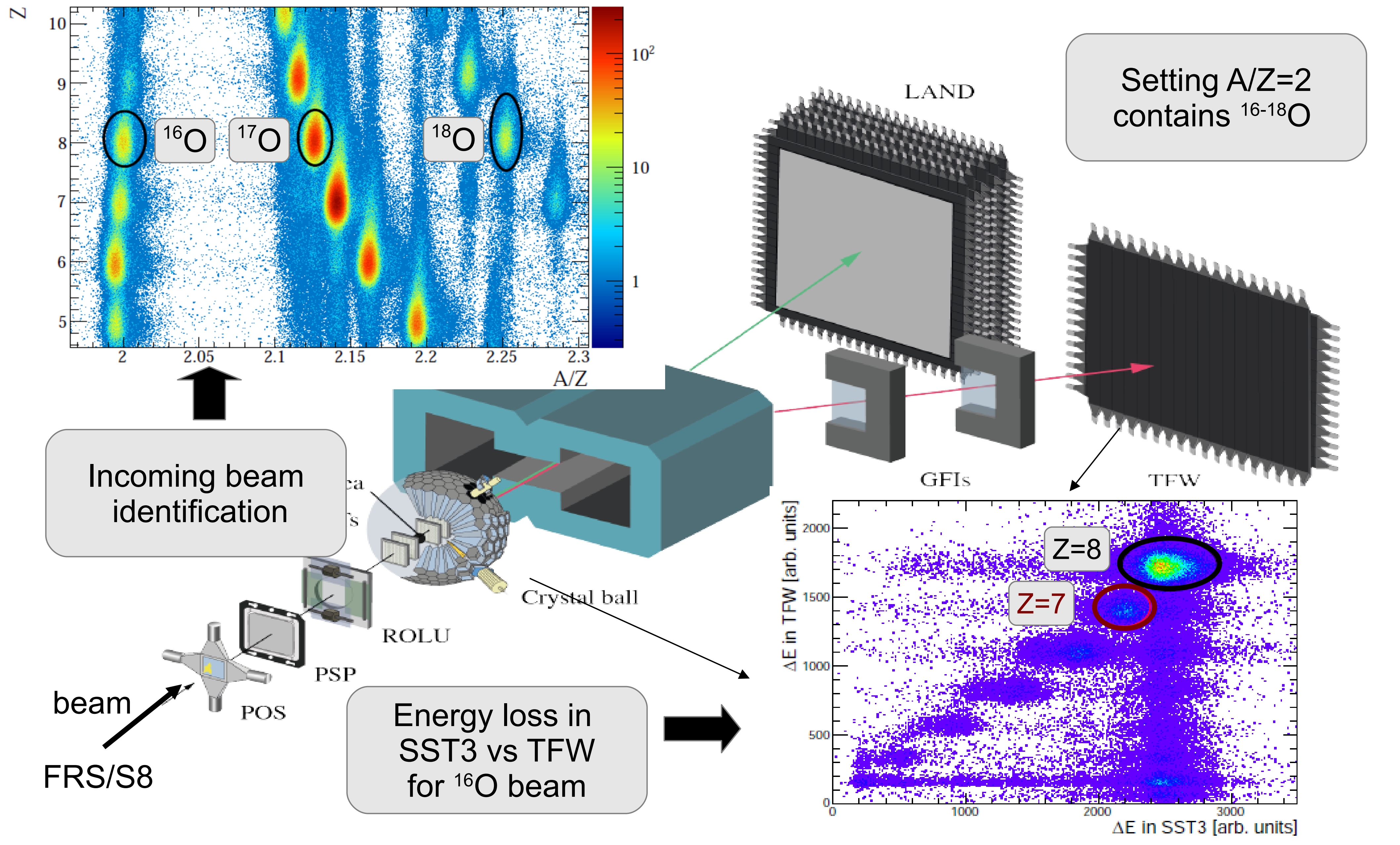


S393 Experiment at R^3B/LAND Setup @ GSI

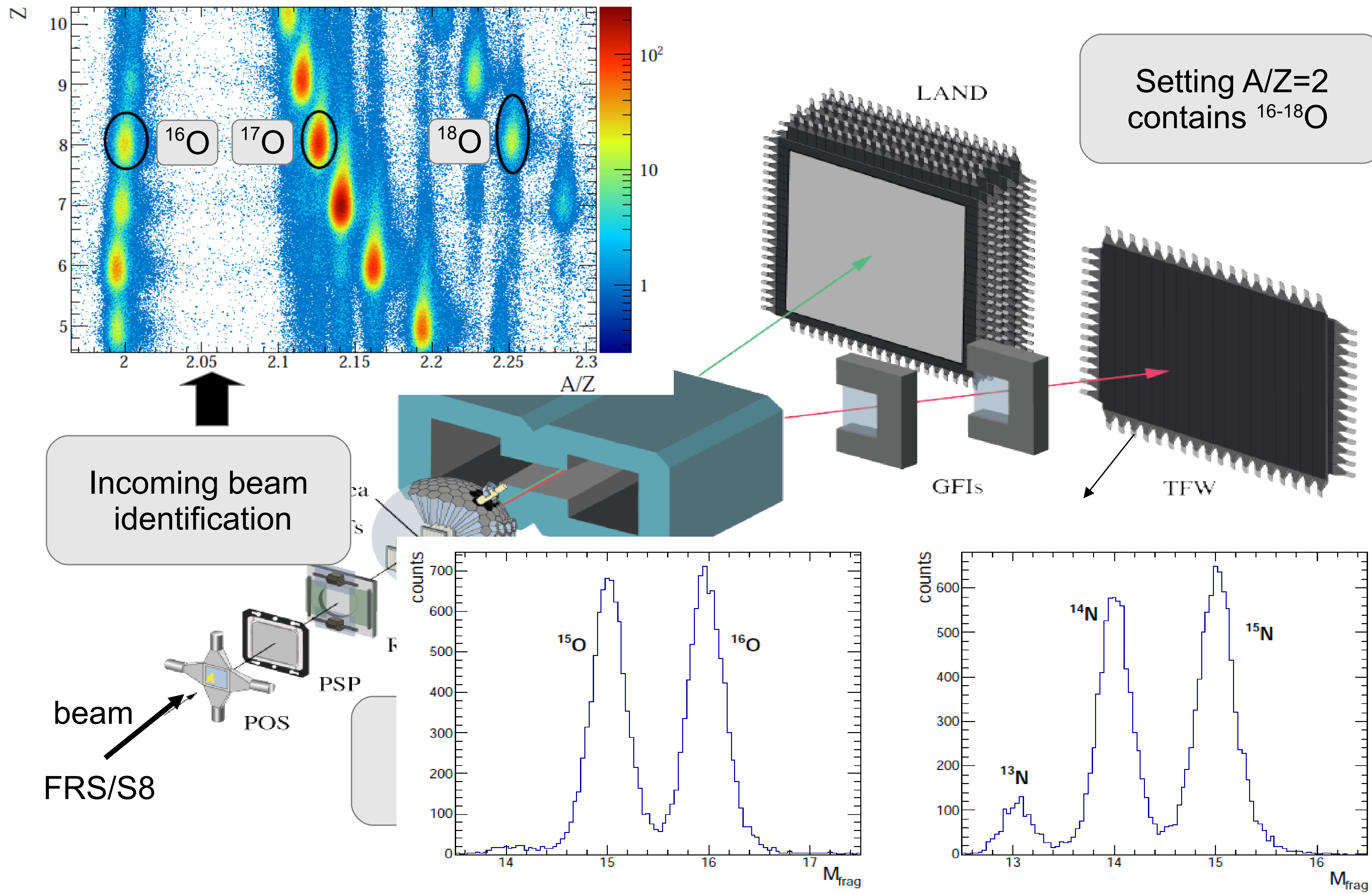


Picture taken from S. Altstadt

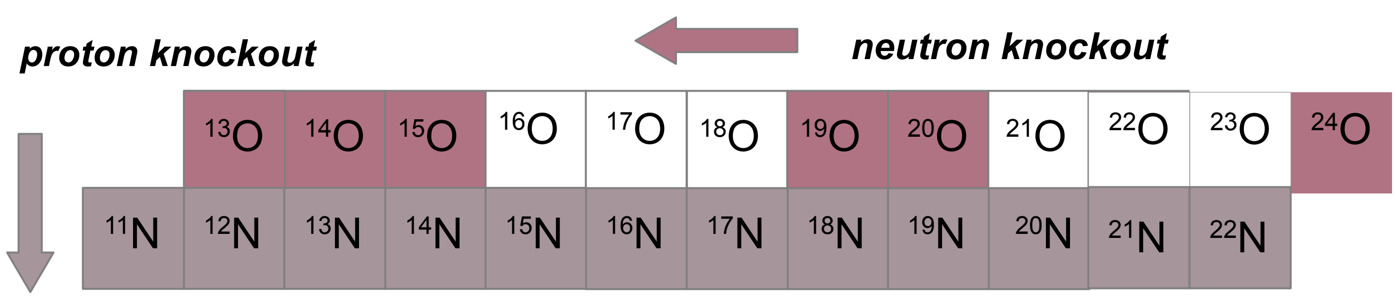
Incoming Beam & Outgoing Fragment Identification



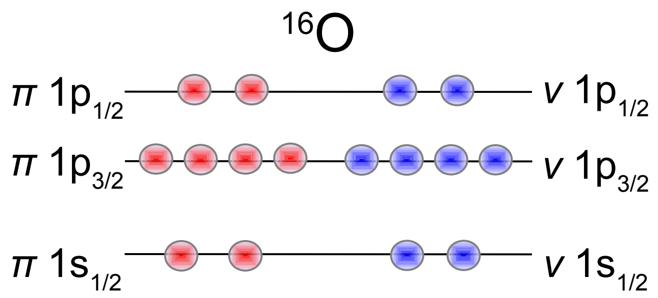
Incoming Beam & Outgoing Fragment Identification



Experimental Results



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



- IPM description of the projectile ground state

- Inclusive cross section with respect to all bound core states

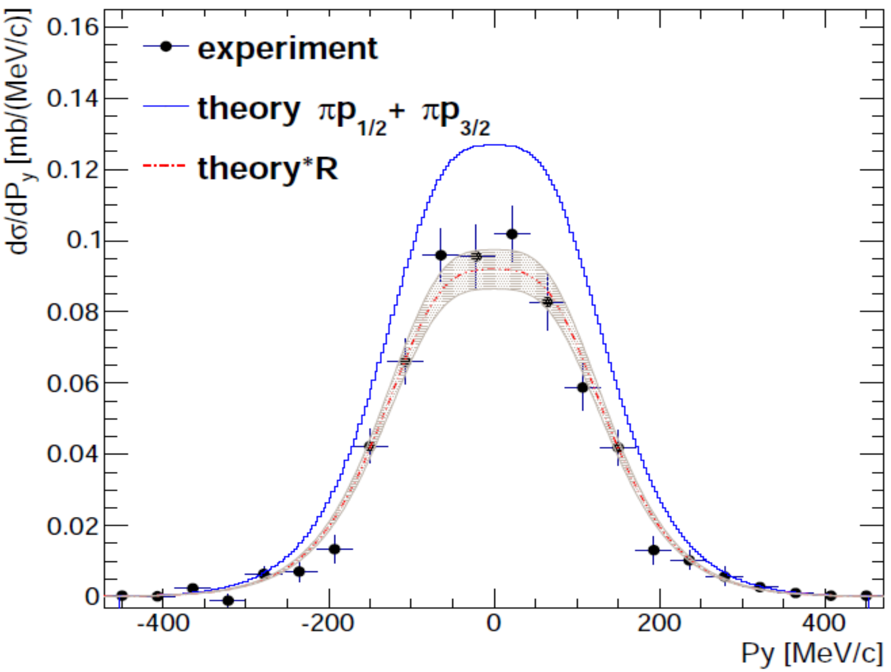
- Reaction theory: C. Bertulani, Eikonal Theory.
T. Aumann, C. Bertulani, J. Ryckebusch Phys. Rev. C88, 064610 (2013)

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

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

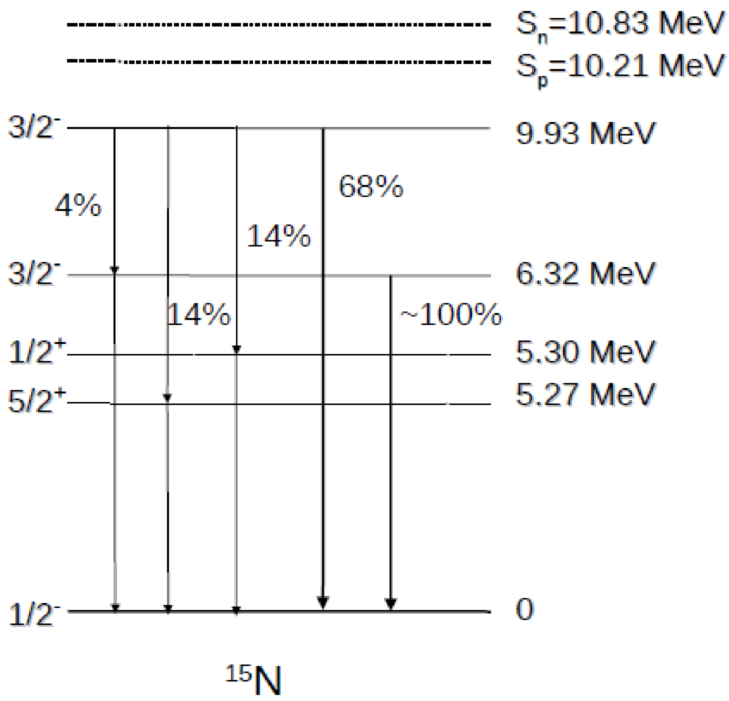
R = 0.65(5)
from
(e,e'p) @ NIKHEF
→ agreement!

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

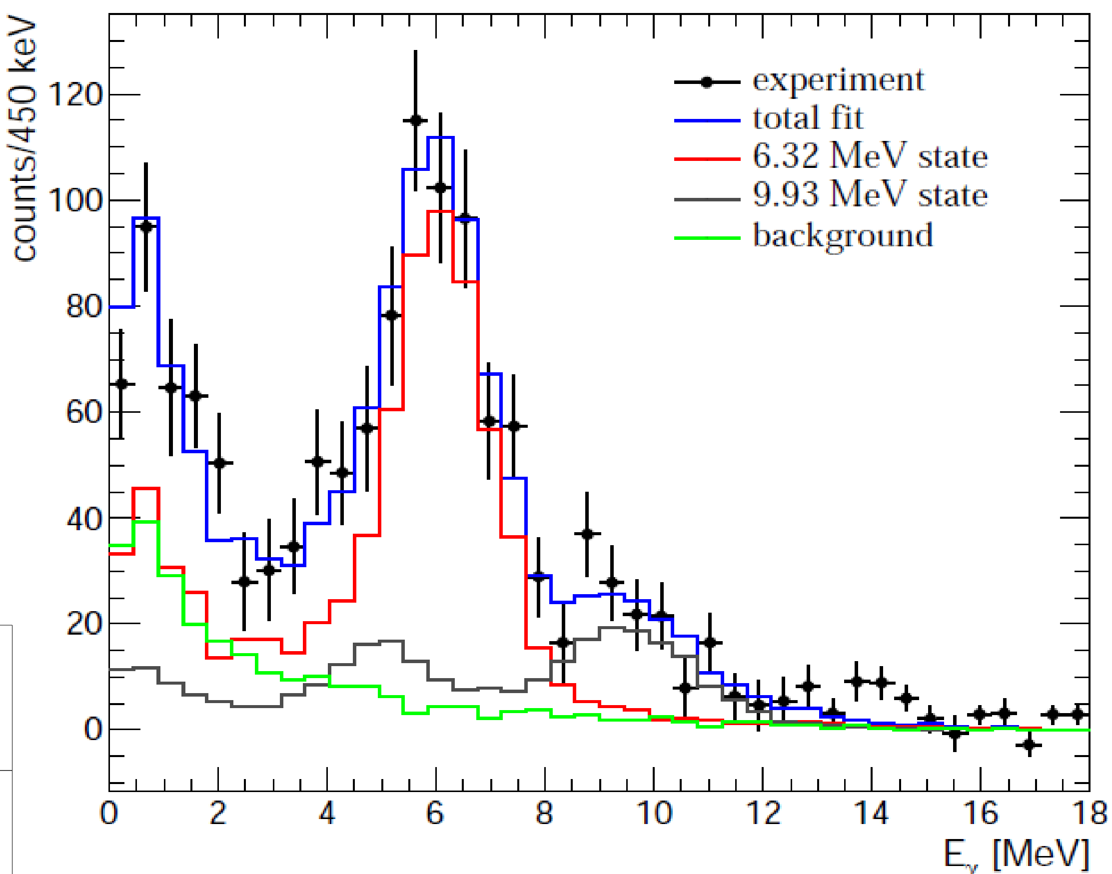


Inclusive P_y distribution for $1p_{1/2}$ and $1p_{3/2}$ shells

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



γ-spectrum in coincidence with $^{16}O(p,2p)^{15}N$



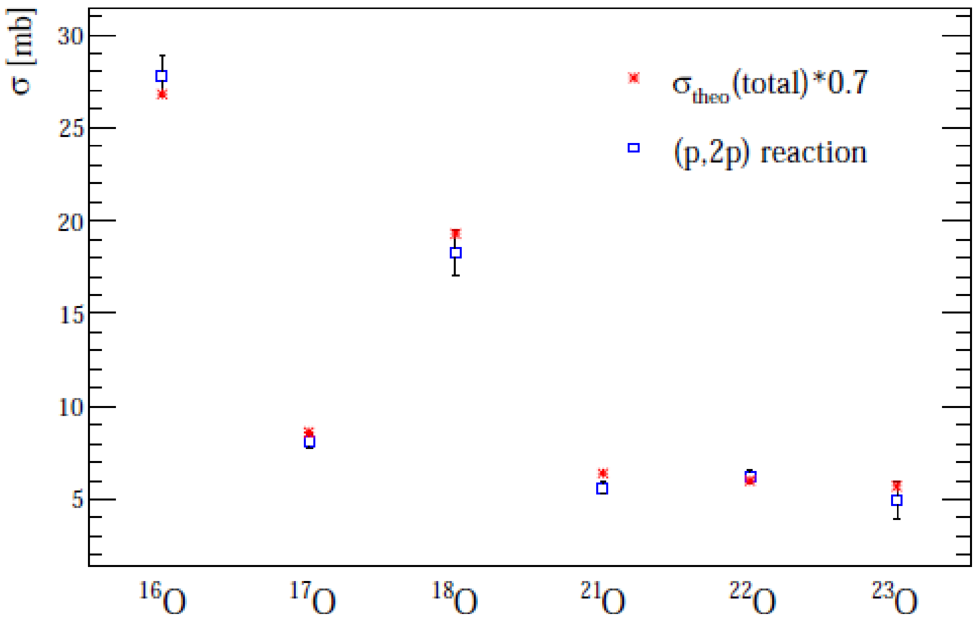
J^π	$1/2^-$ 0.0 MeV	$3/2^-$ 6.3 MeV	$3/2^-$ 9.9 MeV
b (%)	36(5)	47(4)	17(3)
σ_{exp} [mb]	10(2)	13(1)	5(1)
C^2S	1.5(3)	2.1(2)	0.7(1)
C^2S (e,e'p)	1.3(1)	2.4(2)	0.1(2)

Spectroscopic factors deduced from the partial cross sections obtained from the fit of the γ-spectrum

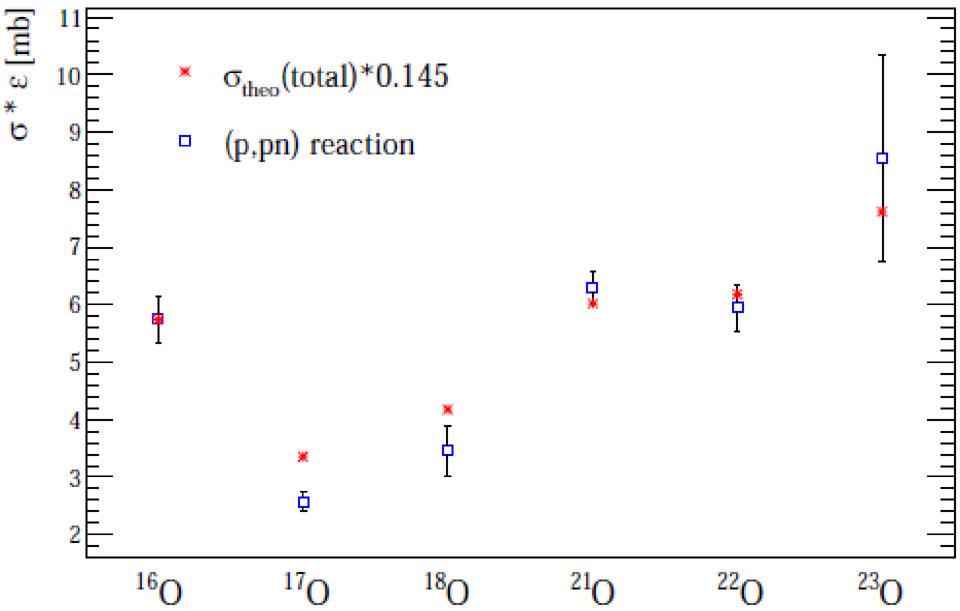
← (e,e'p) @ NIKHEF

Inclusive Cross Sections for Projectiles $^{16-18}O$ and $^{21-23}O$

(p,2p) reaction



(p,pn) reaction



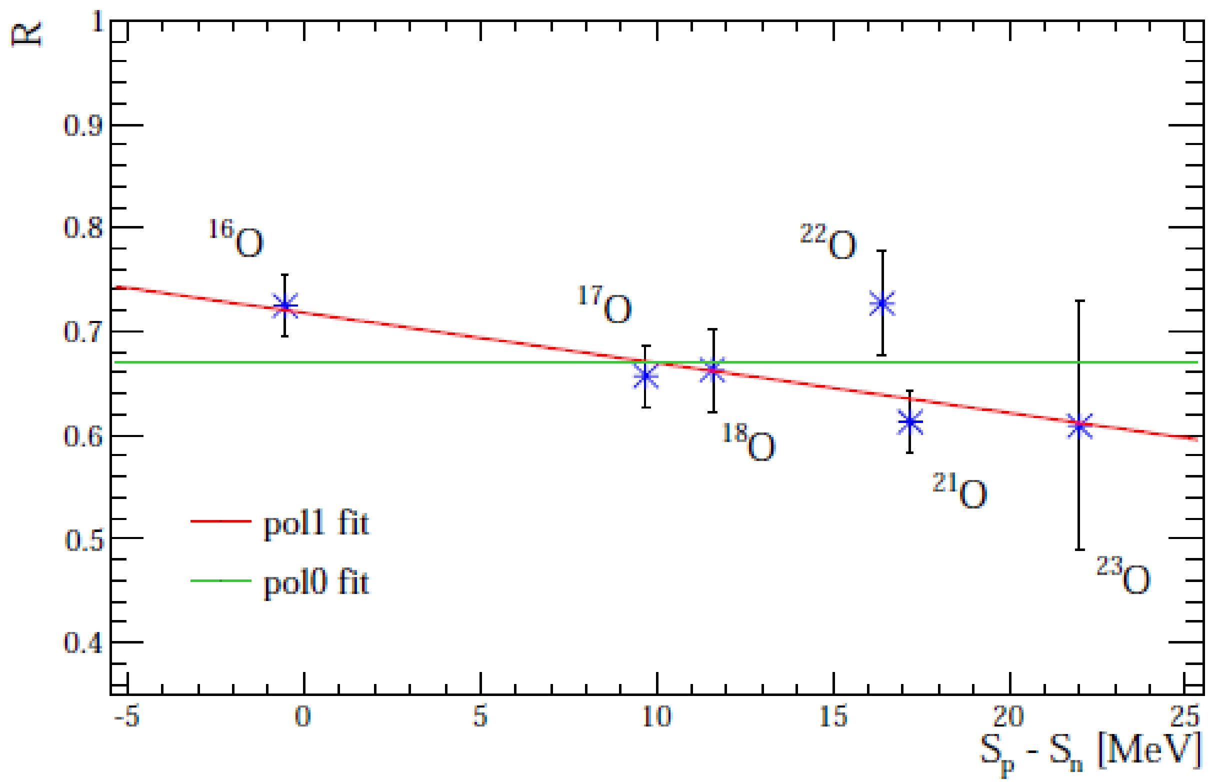
^{16}O and ^{18}O → larger S_n → knockout of $1p_{1/2}$ and $1p_{3/2}$ protons

^{17}O and $^{21-23}O$ → lower S_n → knockout of only $1p_{1/2}$ protons

detector efficiency uncorrected

different contributions from $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$ and $2s_{1/2}$ neutrons

Reduction Factors from (p,2p) Cross Sections



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

(p,2p) reaction

pol0 fit: constant fit
→ reduced $\chi^2 = 1.75$

pol1 fit: polynomial fit
→ reduced $\chi^2 = 0.97$

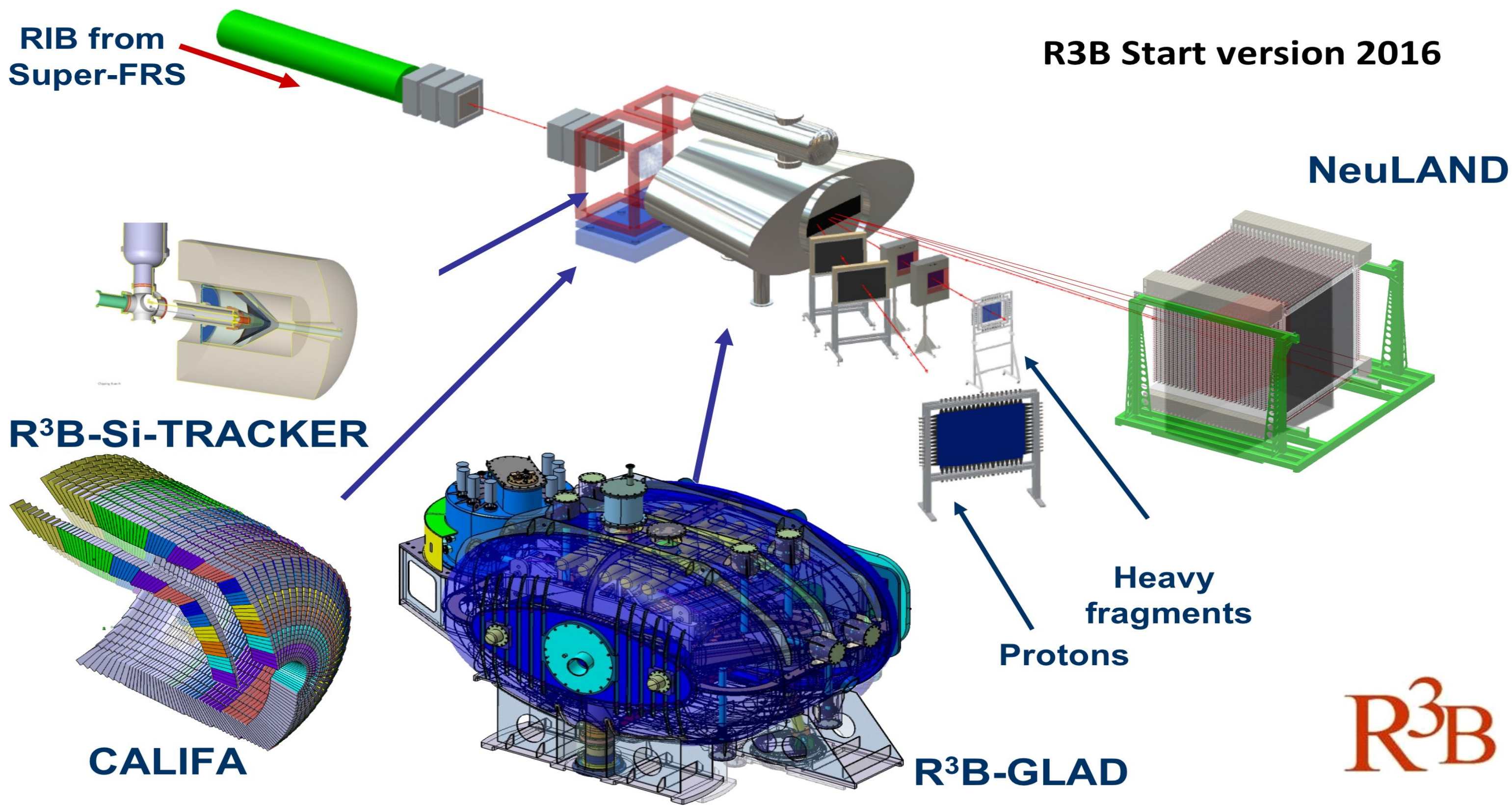
- *A* weak dependency of single-particle strength on isospin asymmetry
- In contrast to the observed trend from one-nucleon removal reactions in low energies using composite targets

Summary

- Quasi-free knockout reactions in inverse kinematics provide a direct tool to obtain spectroscopic information.
- The results for the projectiles $^{16-18}O$ and $^{21-23}O$ have been obtained.
- The reduction factor obtained from $^{16}O(p,2p)^{15}N$ reaction is in agreement with the results from (e,e'p) reaction at NIKHEF facility.
- Only weak dependency of single-particle strength on the isospin asymmetry is observed.
- It is necessary to understand reaction mechanism for knockout of deeply bound states at these low energies.

Outlook

- Systematic analysis for entire Oxygen isotopic chain
- A discussion of the results for the (p,pn) channel not attempted due to the more challenging estimation of the efficiency for neutron detection.
- Development of optimized detector system for the future R^3B (Reactions with Relativistic Radioactive Beams) program at FAIR.



Thanks

for your attention

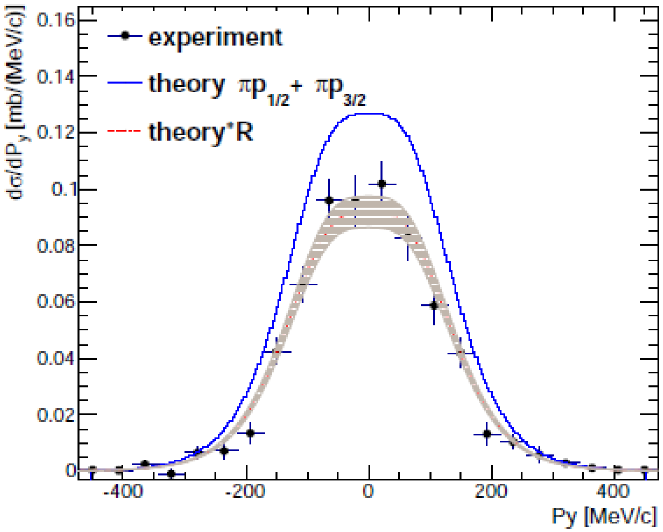
The R3B Collaboration

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; Korsheninnikov, Alexei; Korten, Wolfram; Krasznahorkay, Attila; Kratz, Jens Volker; Kresan, Dima; Anatoli Krivchitch; Kroell, Thorsten; Krupko, Sergey; Kruecken, Reiner; Kulessa, 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; Marganiec, Justyna; Meister, Mikael; Mittig, 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; Reifarth, 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; Turrion, 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, Miroslaw; Zilges, Andreas;

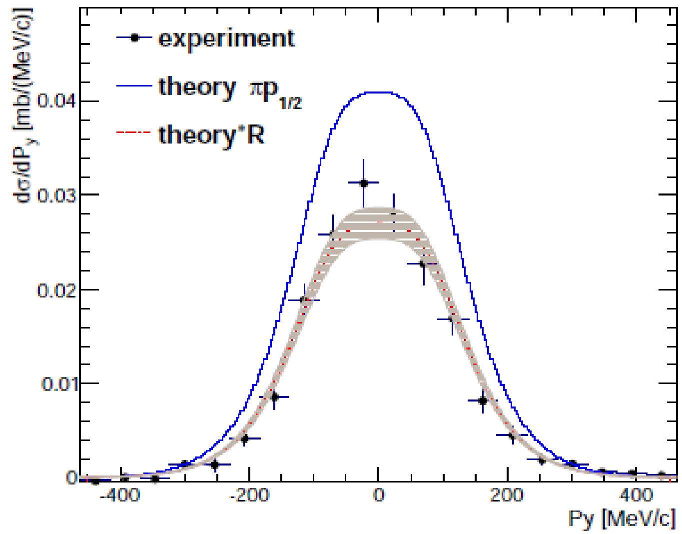
Backup Slides

y-projection of transverse momentum distributions

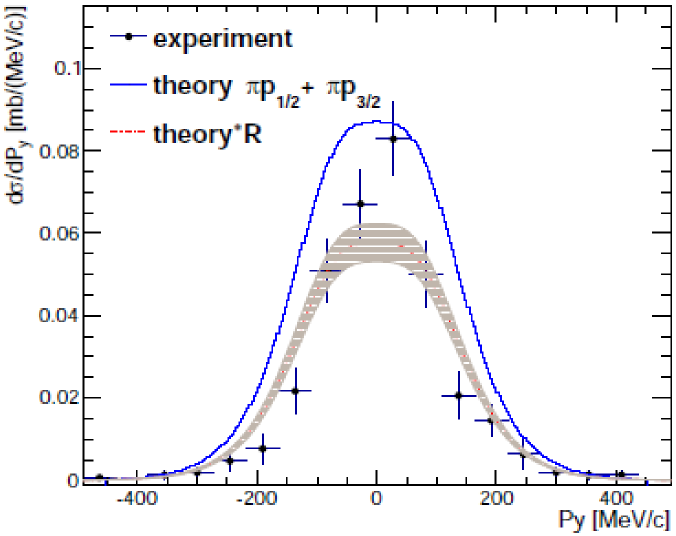
$^{16}O(p,2p)^{15}N$



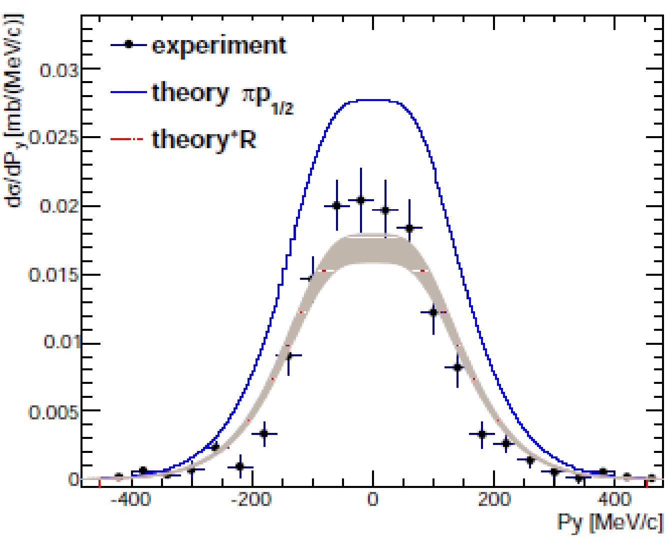
$^{17}O(p,2p)^{16}N$



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



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



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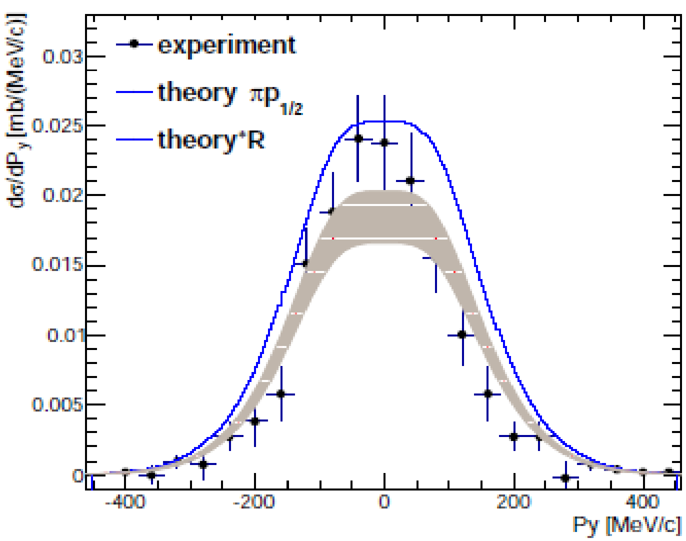

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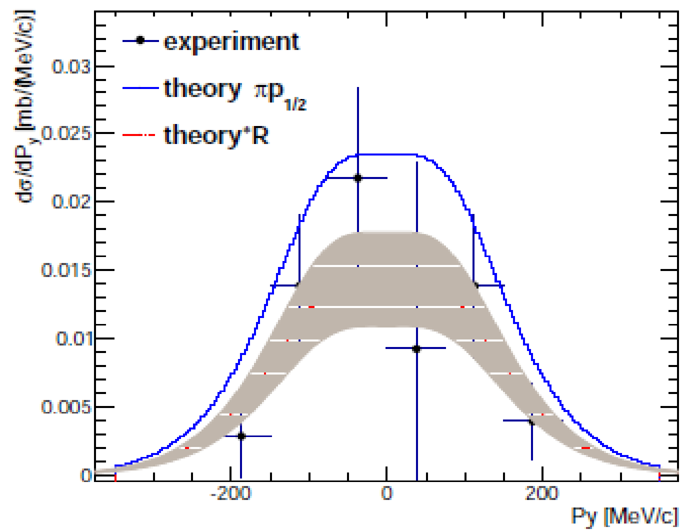
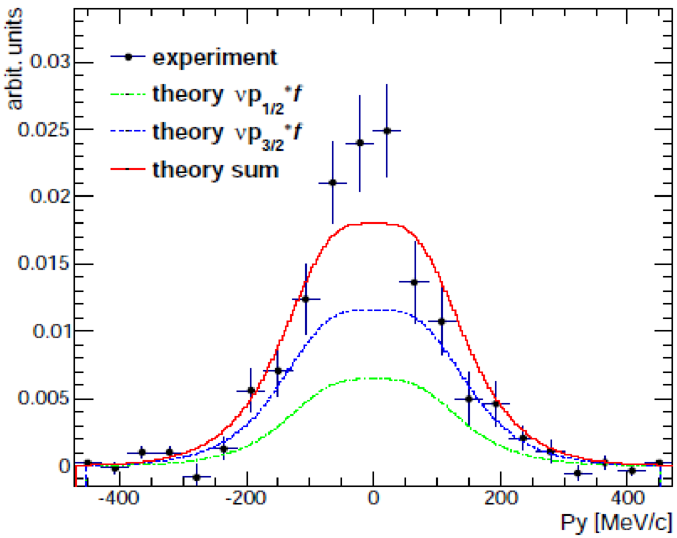


y-projection of transverse momentum distributions

$^{16}O(p,pn)^{15}O$



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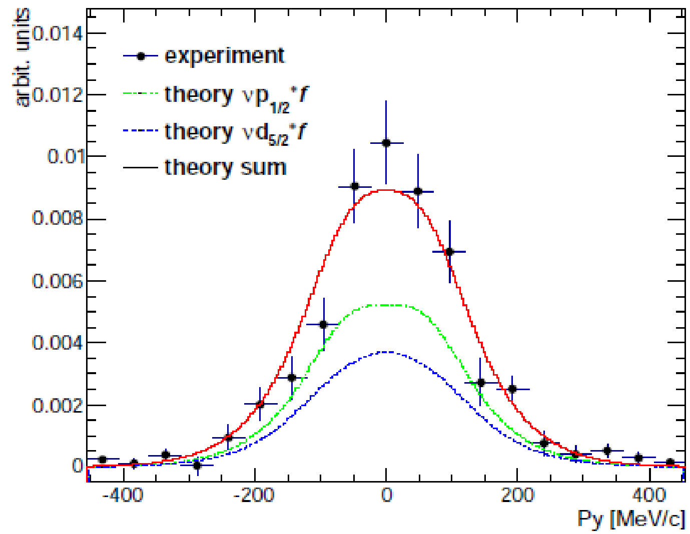
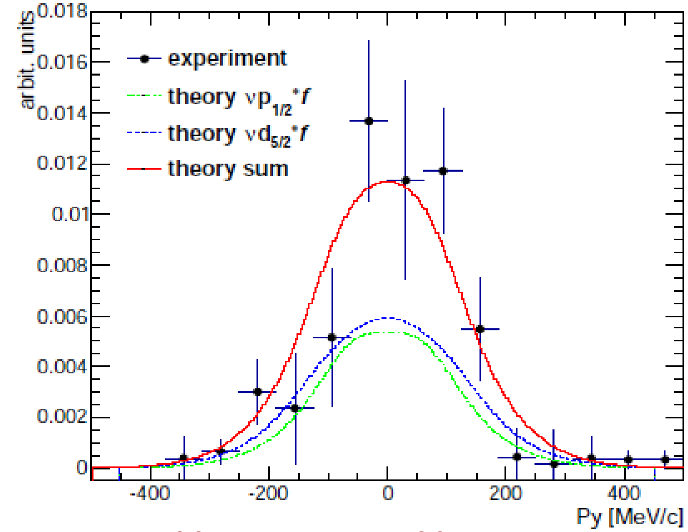
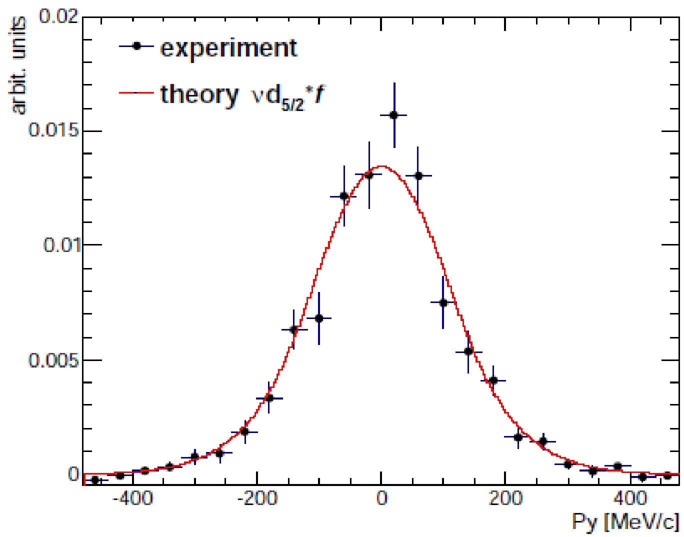


$^{18}O(p,pn)^{17}O$



$^{21}O(p,pn)^{20}O$



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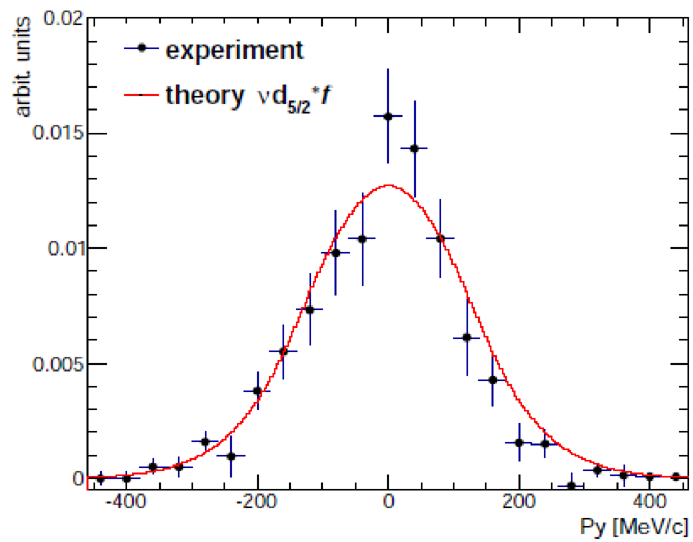
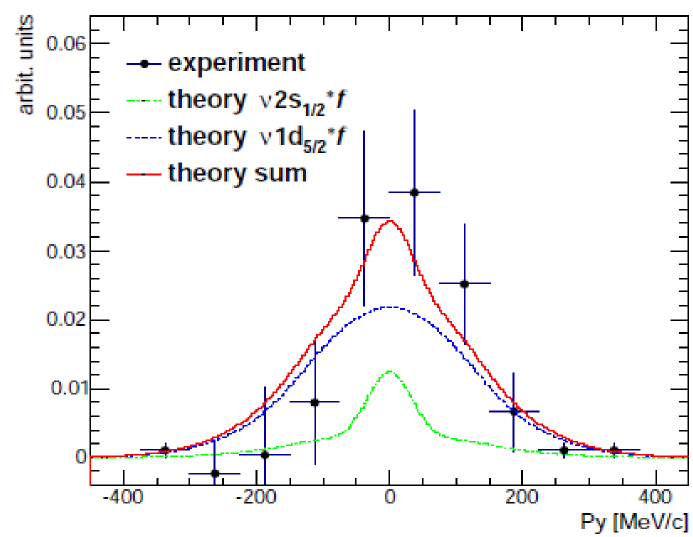
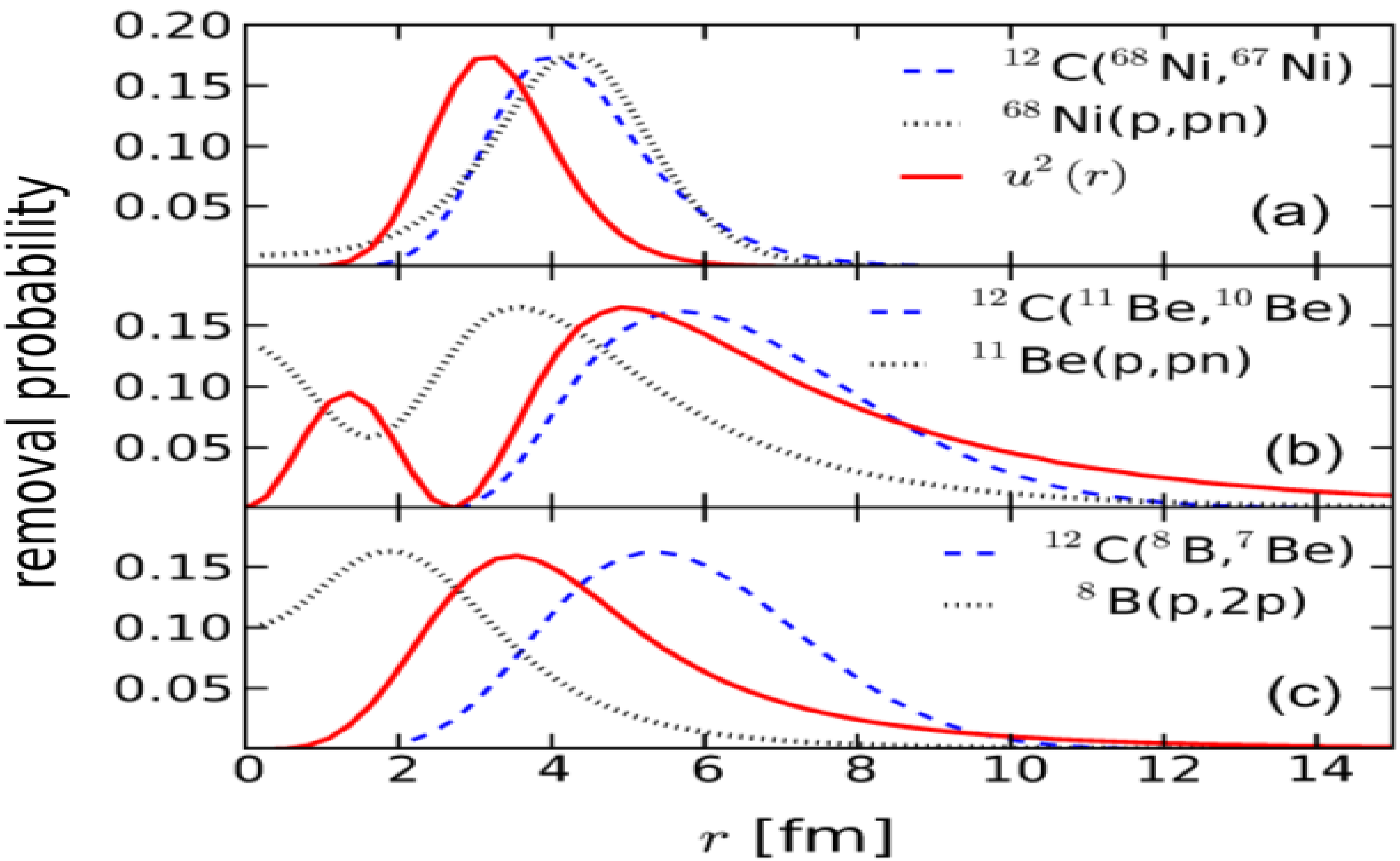


$^{23}O(p,pn)^{22}O$



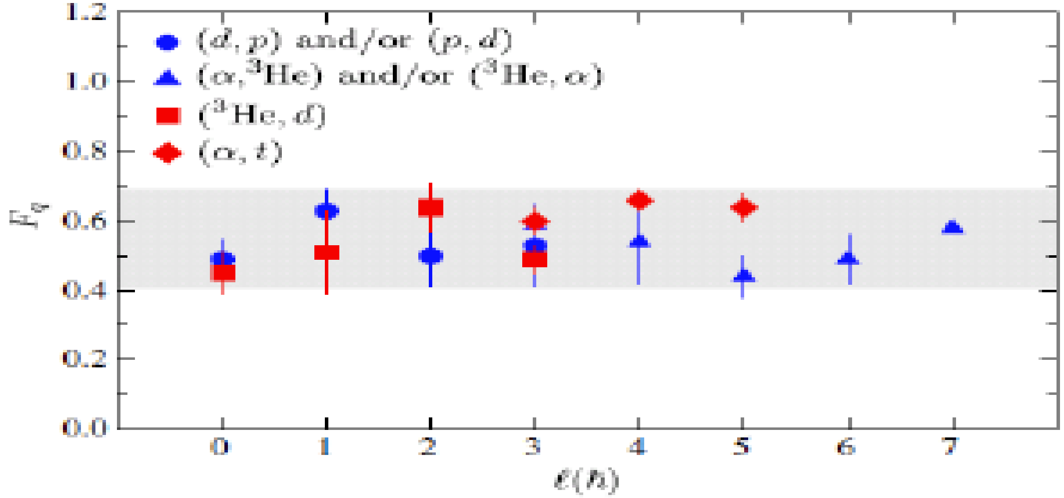
Separation energies of Oxygen & Nitrogen Isotopes

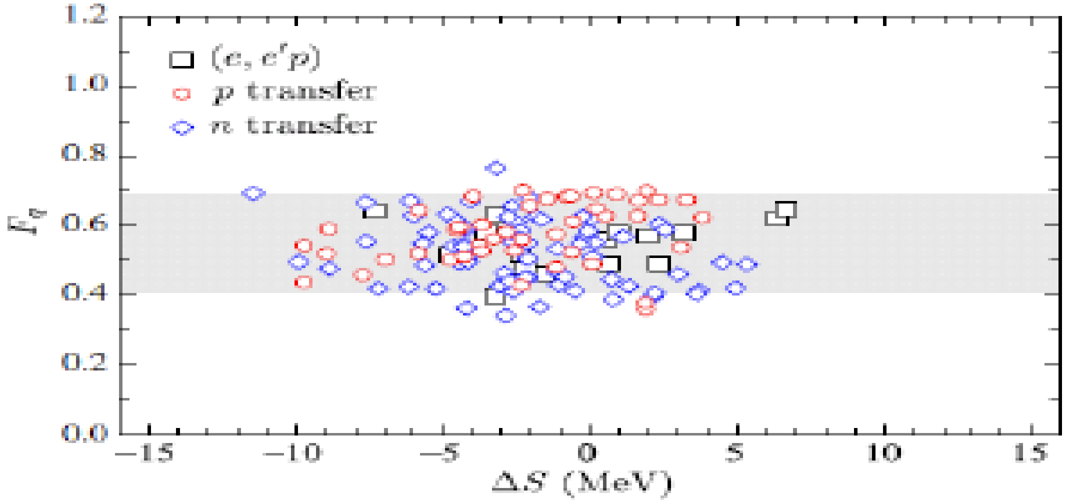
Isotope	S_n[MeV]	S_p[MeV]	Isotope	S_n[MeV]	S_p[MeV]
^{15}O	13.2	7.3	^{15}N	10.9	10.2
^{16}O	15.7	12.1	^{16}N	2.5	11.5
^{17}O	4.1	13.8	^{17}N	5.9	13.1
^{18}O	8.0	15.9	^{18}N	2.8	15.2
^{19}O	4.0	17.1	^{19}N	5.3	16.4
^{20}O	7.6	19.4	^{20}N	2.2	18.4
^{21}O	3.8	21.0	^{21}N	4.6	19.6
^{22}O	6.9	23.3	^{22}N	1.3	21.2
^{23}O	2.7	24.7	^{23}N	1.7	22.2



Aumann,Bertulani,Ryckebusch,

Transfer reactions





B.P. Kay, *et.al.* Phys. Rev. Lett. 111, 042502 (2013)