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

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for R³B Collaboration

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TECHNISCHE UNIVERSITÄT DARMSTADT

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GSI

R³B

Outline

- Quasi-free (p,2p) on Oxygen Isotopes
  - Introduction
  - Experimental Setup
  - Analysis Results
- Fission Reactions via Quasi-free (p,2p)
- Summary & Outlook

Single-Particle Strength

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

- Reduction factor

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

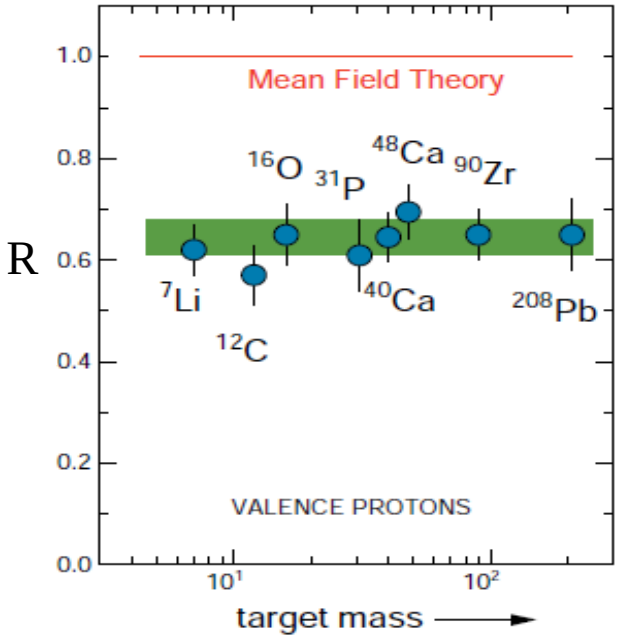
  relative to the IPM!

- 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 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?

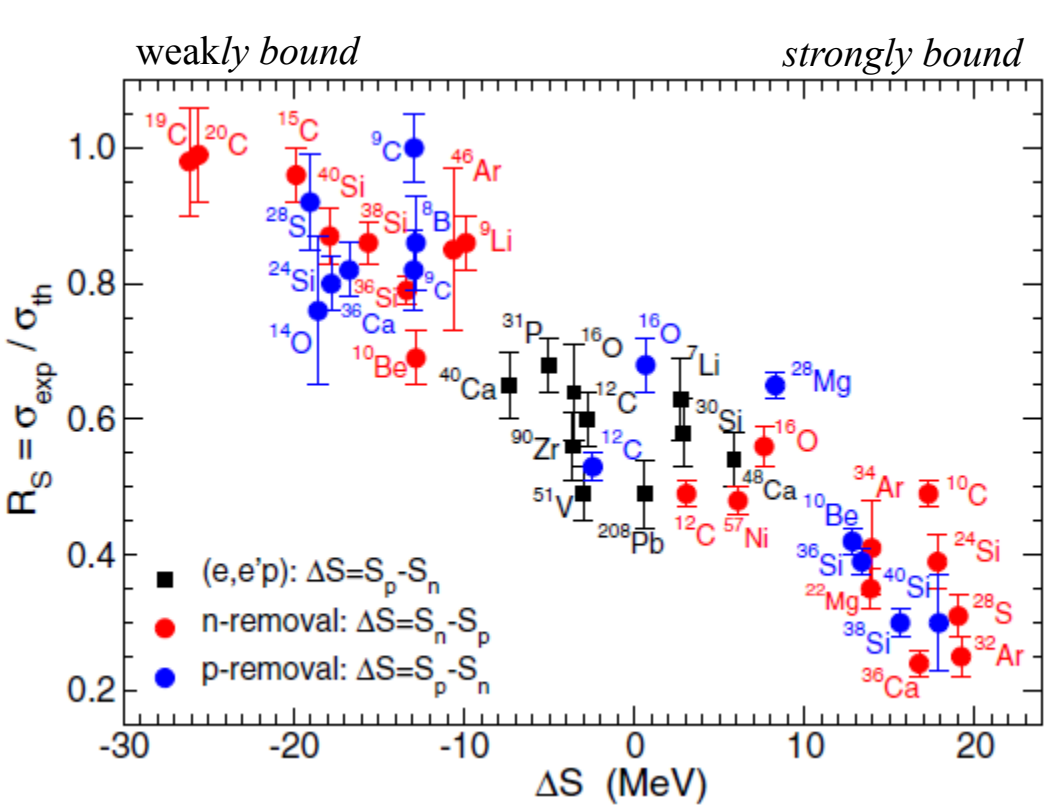
  Quenching of single-particle strength in strongly bound states?

  → 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



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

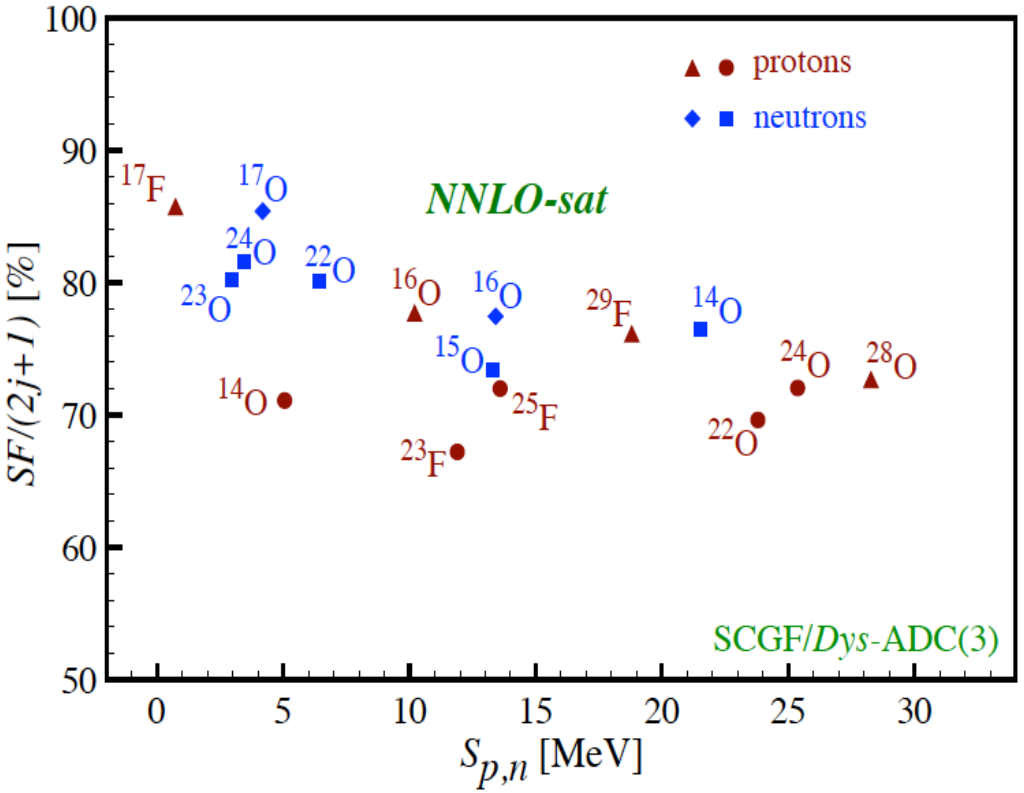
Reduction factor relative to a certain Shell Model:

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

correlations are partially included!

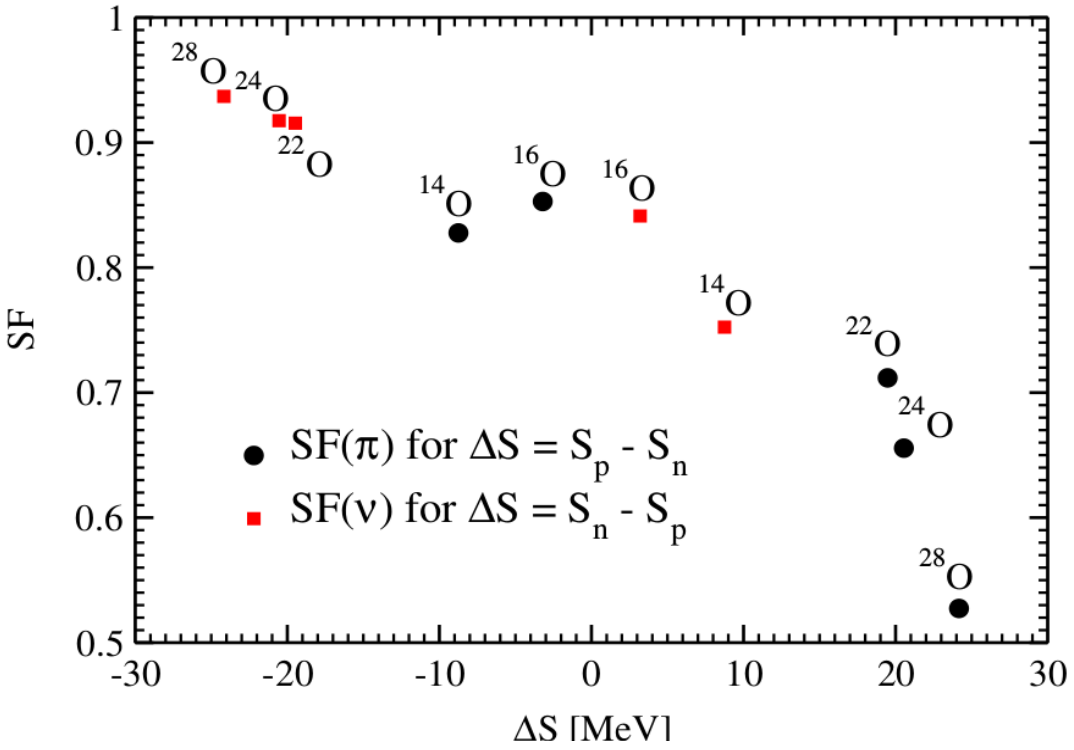
Ab-initio Theory: Weak Dependence

- SCGF with chiral NNLO-sat interactions
- weak ΔS dependence from 0.6 to 0.9



C. Barbieri, private communication (July/2016).

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

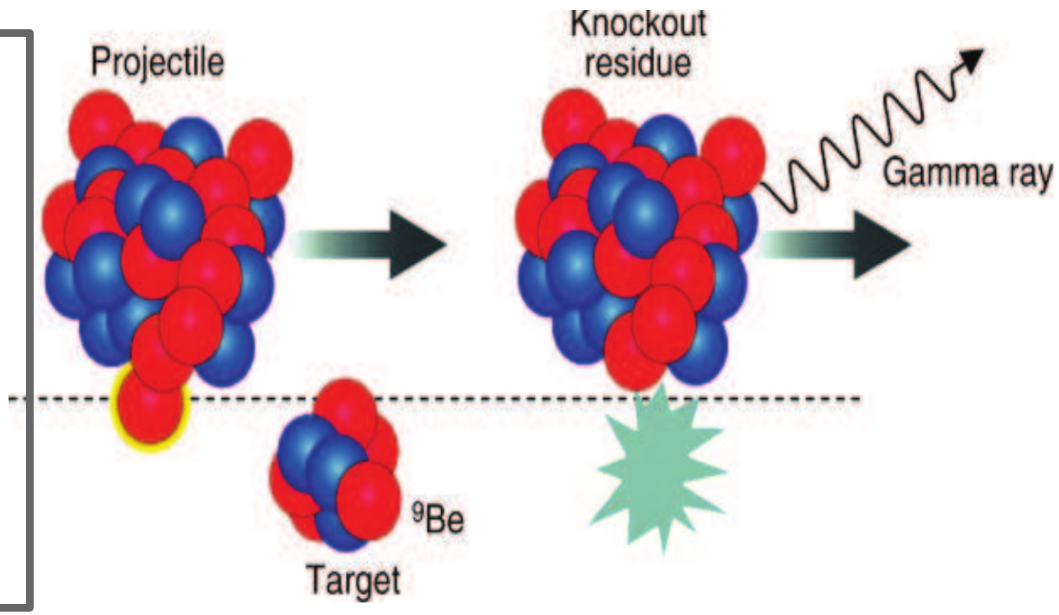


Jensen et al. Phys. Rev. Lett. 107, 032501 (2011)

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 ~ 100MeV/u
- nucleon from projectile scattered
- eikonal & sudden approximations
- strong absorption → surface localized



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

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

residue momentum→ angular momentum ℓ of removed nucleon

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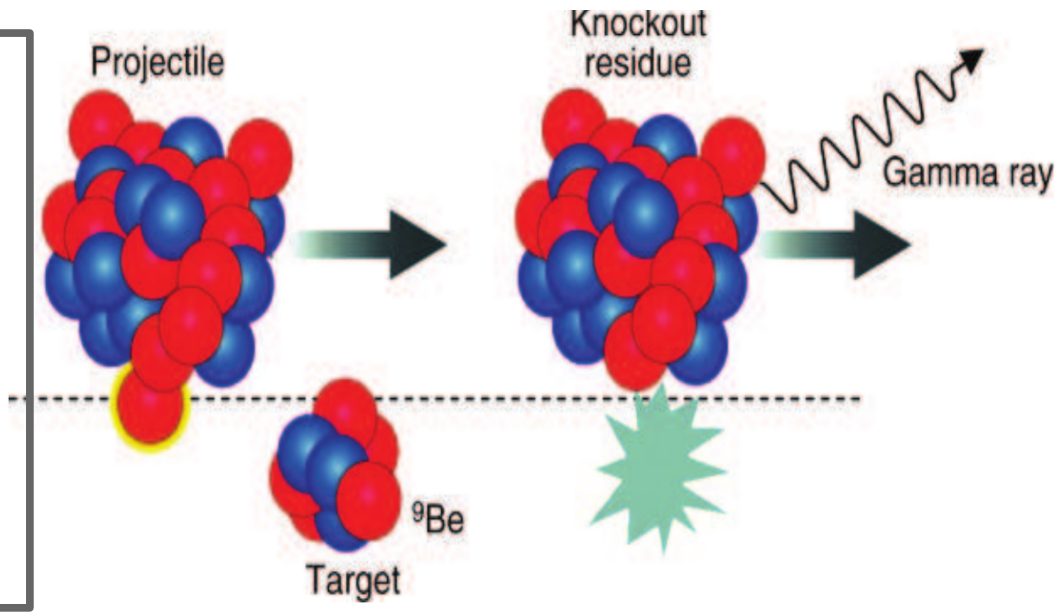

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Measurements — Deduced quantities

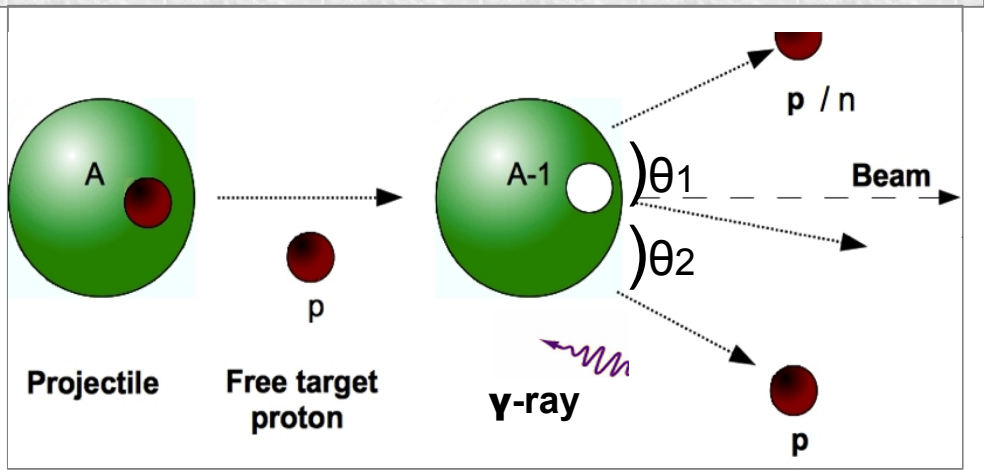
- cross section → reduction/spectroscopic factor
- Momentum distribution → angular momentum ℓ
- γ-ray spectroscopy → selection of final channel

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

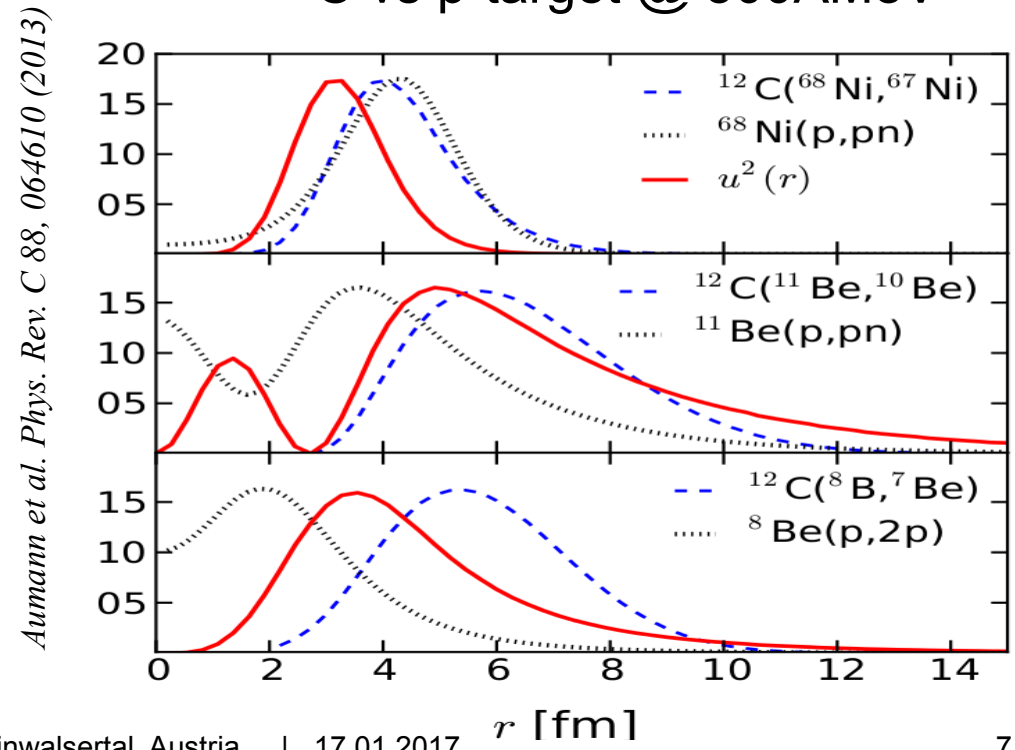
residue momentum→ angular momentum ℓ of removed nucleon

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)



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



Complementary Approach: Quasi-free Scattering at High Energies

- proton target → quasi-free NN reaction and more sensitivity to deeply bound states

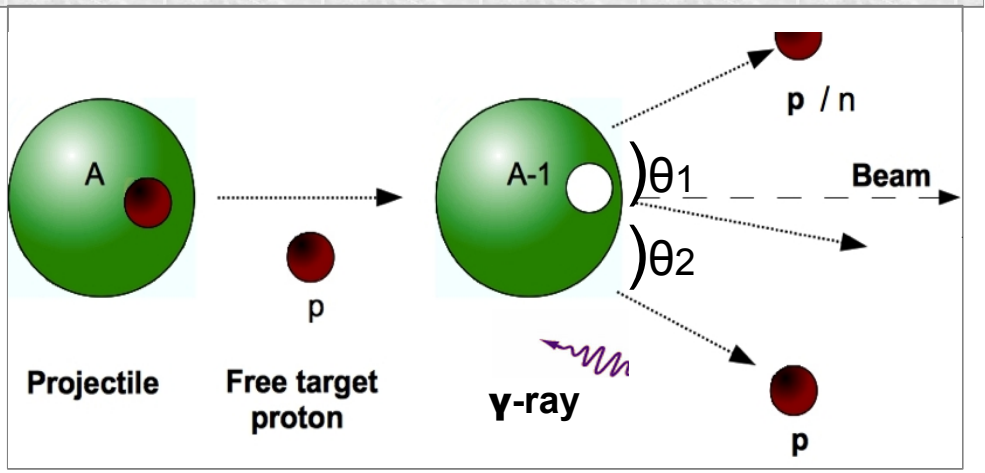
- Relativistic energies (0.2-1 GeV/u)
→ sudden approximation:
fast reaction (10^{-23} s) and spectator core
→ weaker absorption in nucleus
→ free NN cross section is min (~300 MeV)

- eikonal approximation
→ momentum of residue corresponds to momentum of knocked nucleon

- projectile and target nucleon scattered

$P_{A-1} = - P_{p/n}$
residue momentum→ angular momentum ℓ of removed nucleon

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



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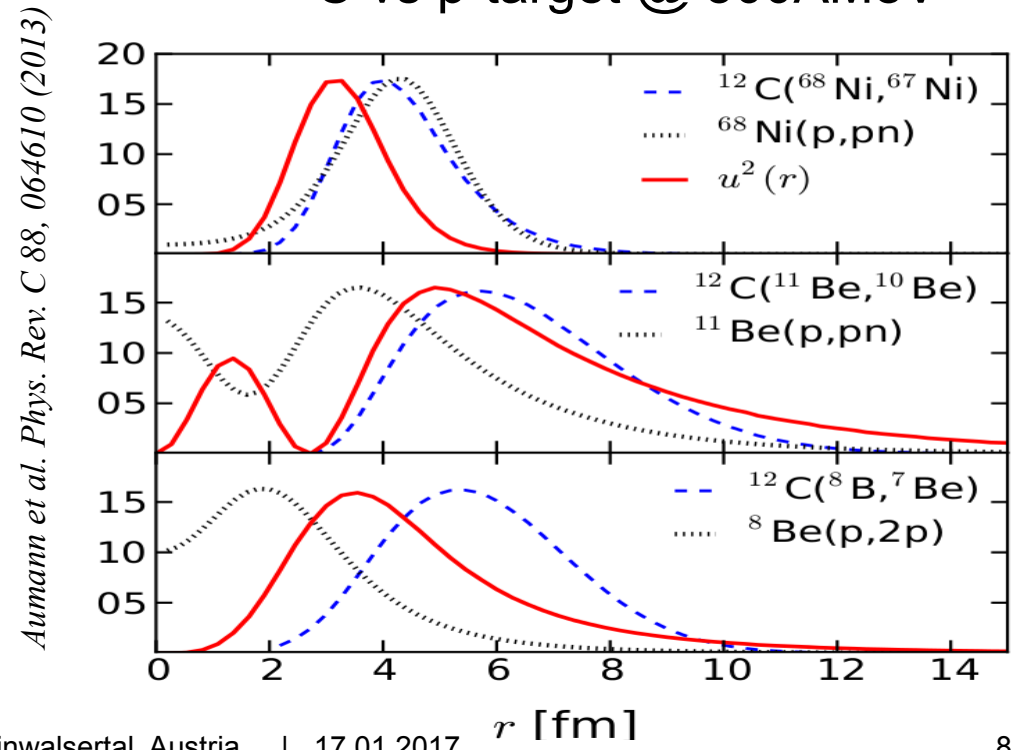
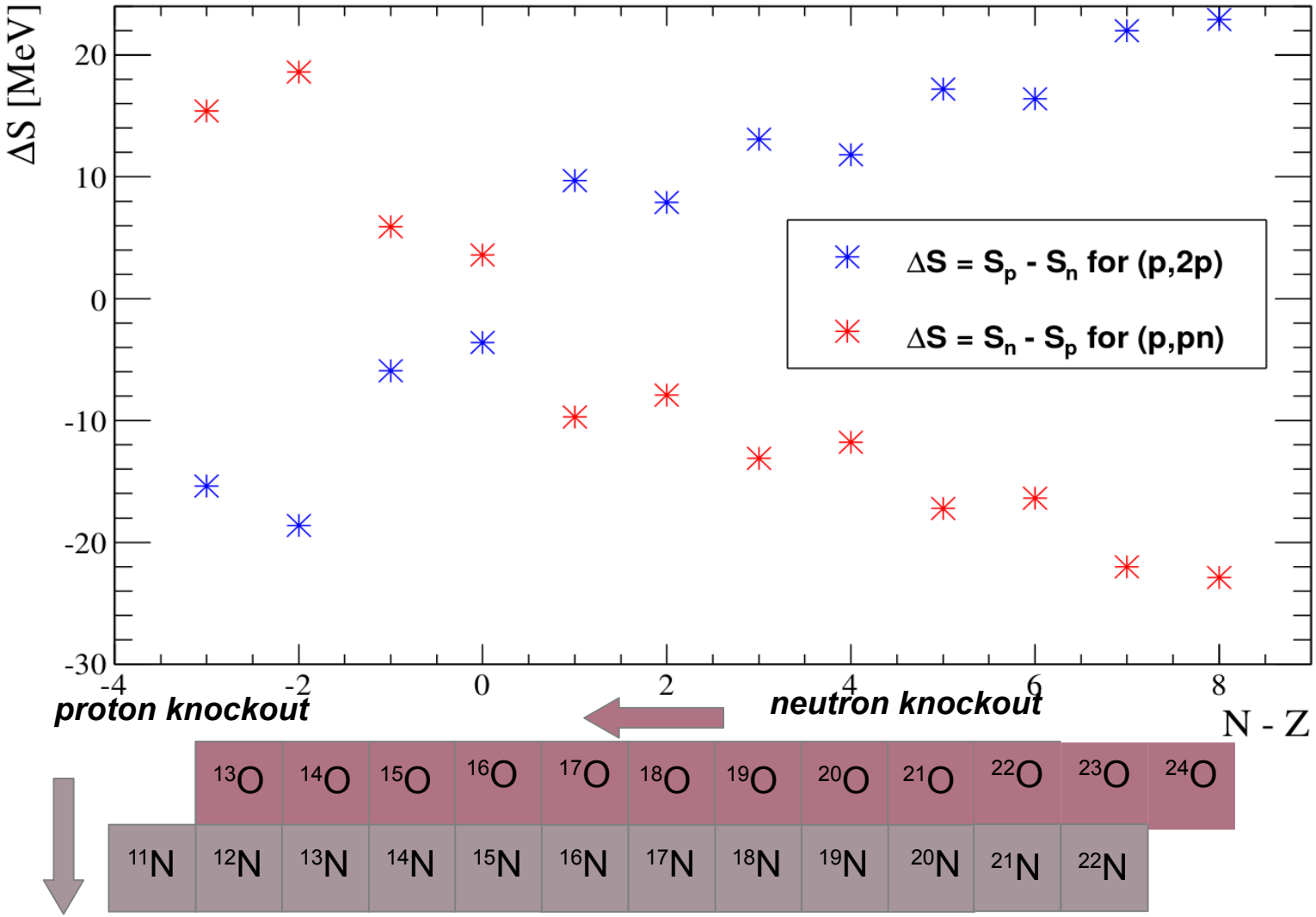


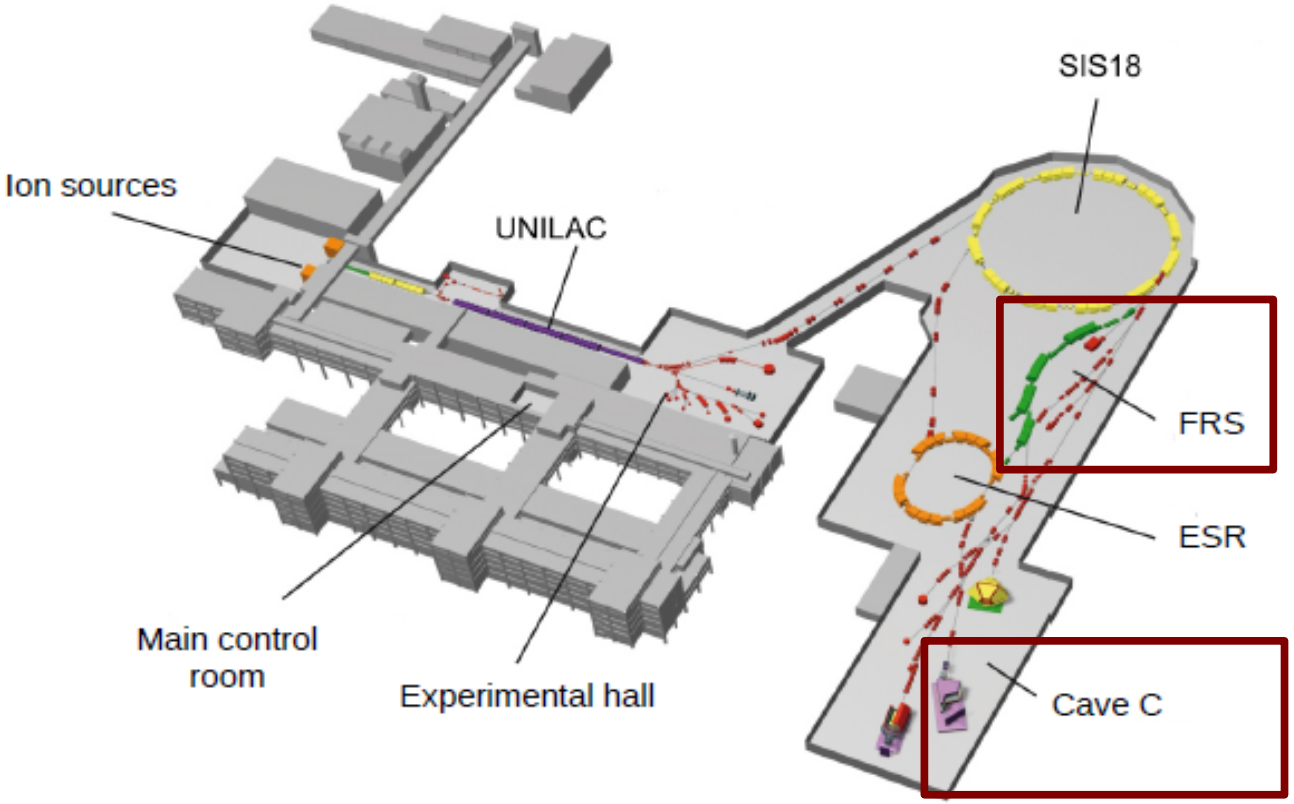
Oxygen Isotopic Chain

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

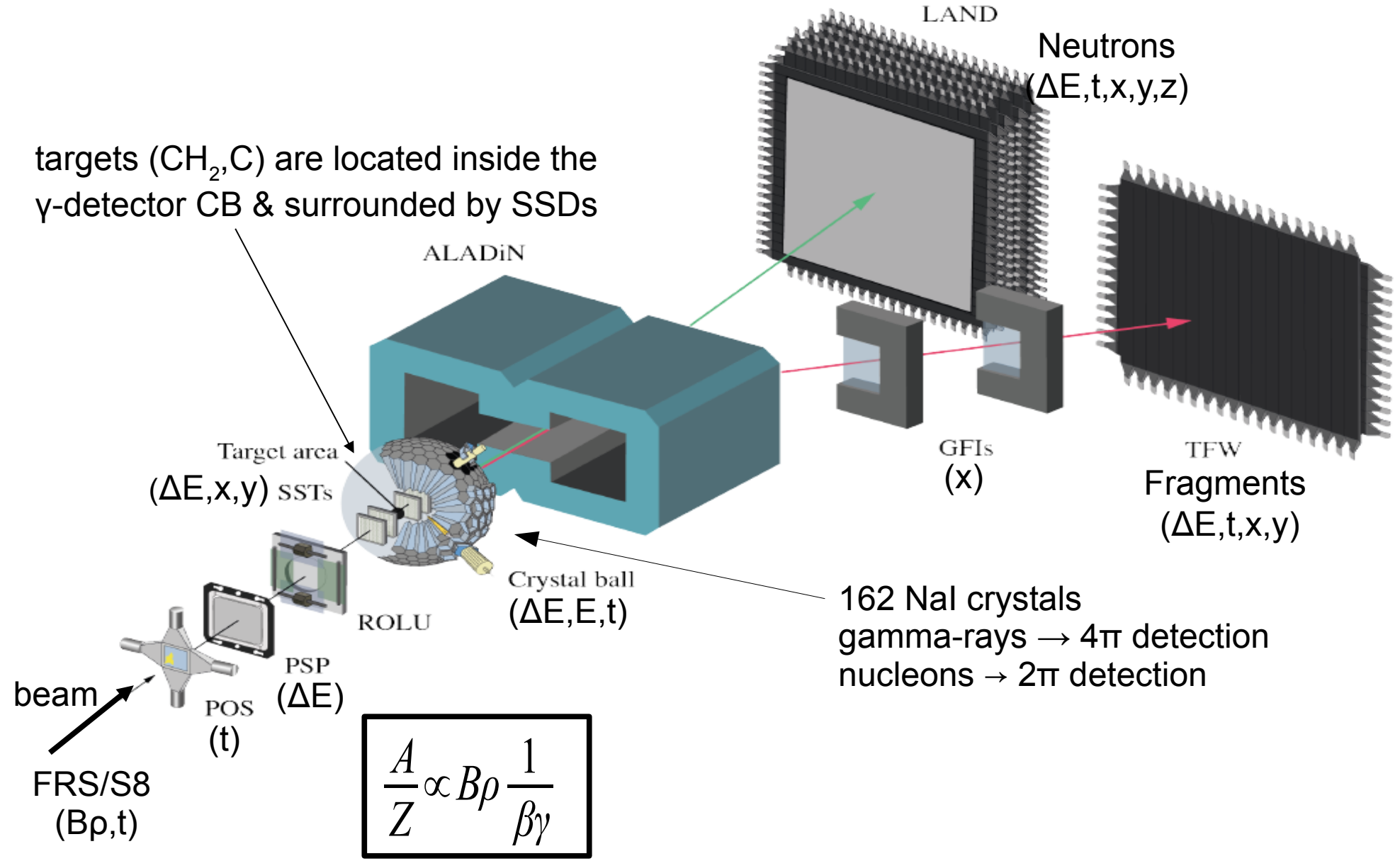


GSI Accelerator Facility

- 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) by in-flight method
- Secondary beam $^{13\text{-}24}$O delivered to Cave C

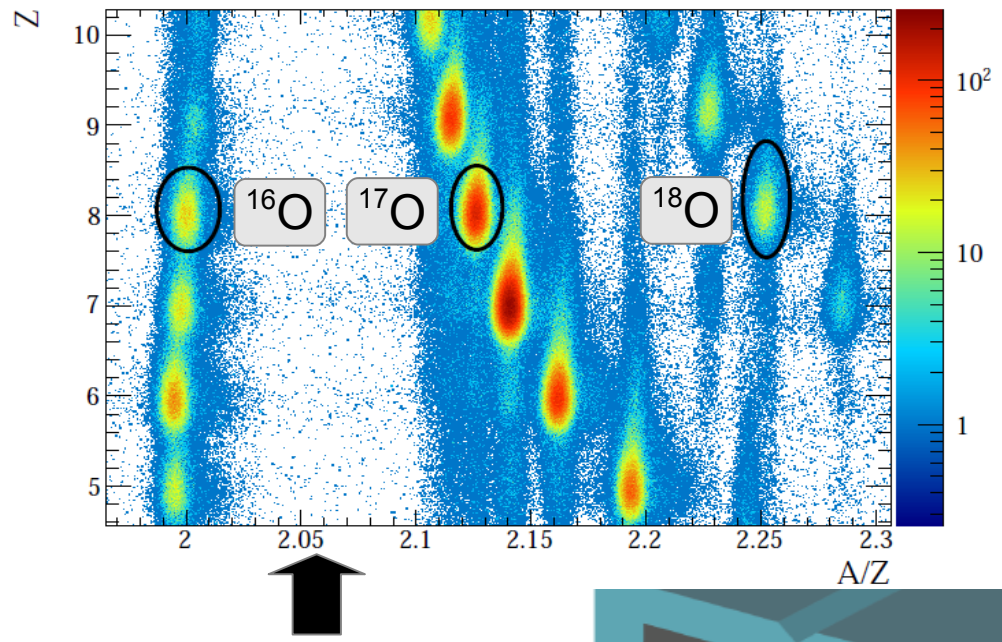


S393 Experiment at R^{3}B/LAND Setup @ GSI



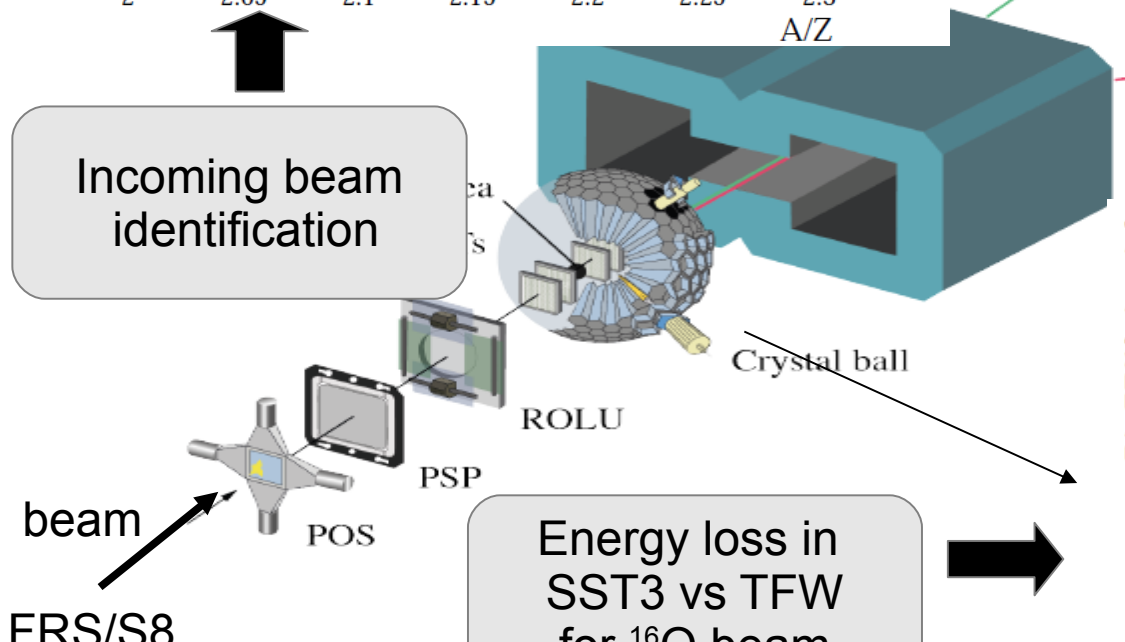
Picture taken from S. Altstadt

Incoming Beam & Outgoing Fragment Identification

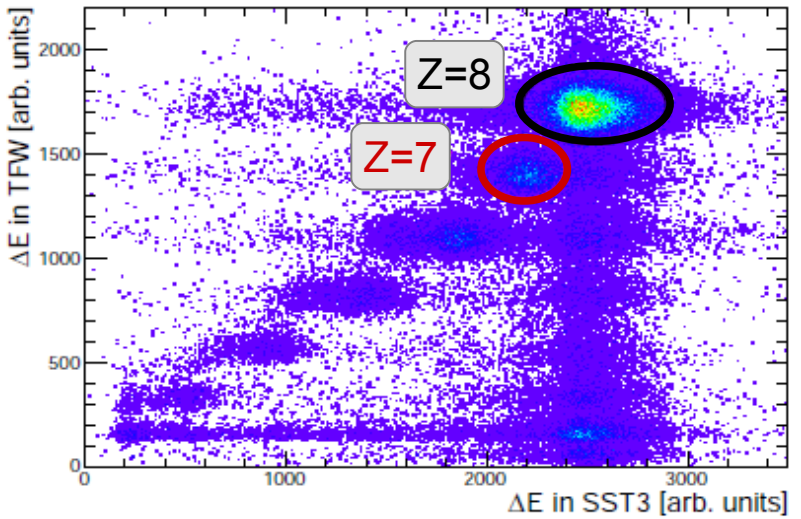


Setting A/Z=2 contains $^{16\text{-}18}$O

Incoming beam identification



Energy loss in SST3 vs TFW for ^{16}O beam



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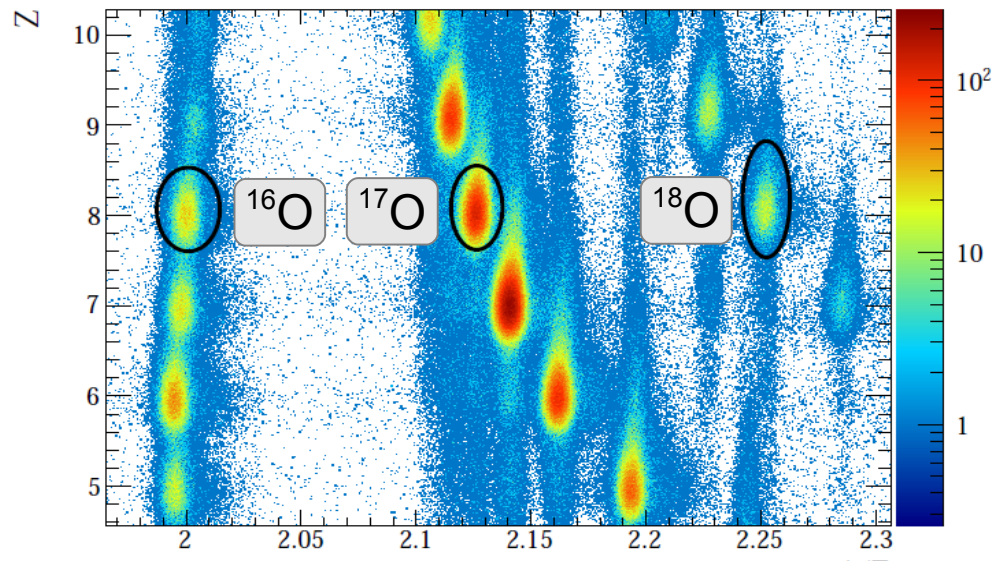

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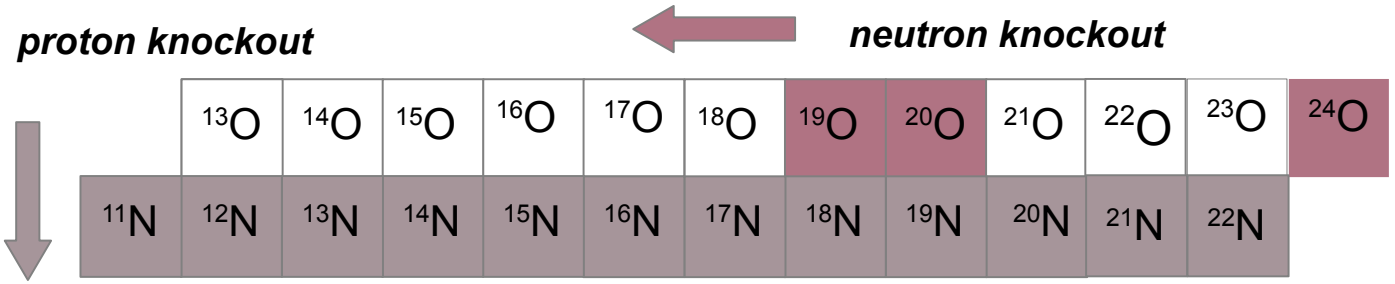
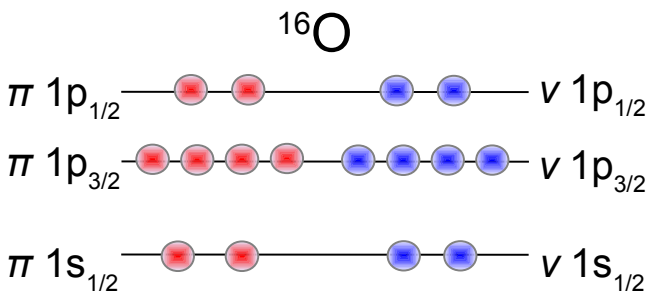
Experimental Results



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



- Reaction theory: C. Bertulani, eikonal theory

T. Aumann, C. Bertulani, J. Ryckebusch Phys. Rev. C88, 064610 (2013)

- Multiple scattering → Glauber model
- Absorption → complex optical potential
- Only bound core excited states considered

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
$R = \sigma_{exp}/\sigma_{theo(IPM)}$

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

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

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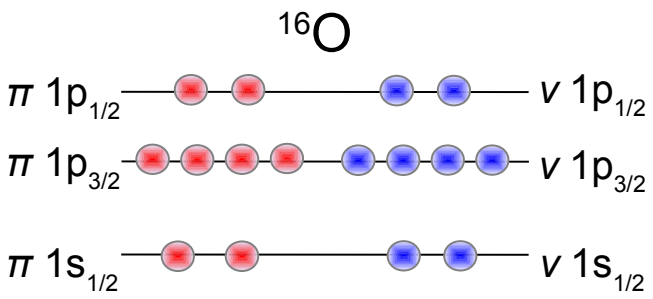

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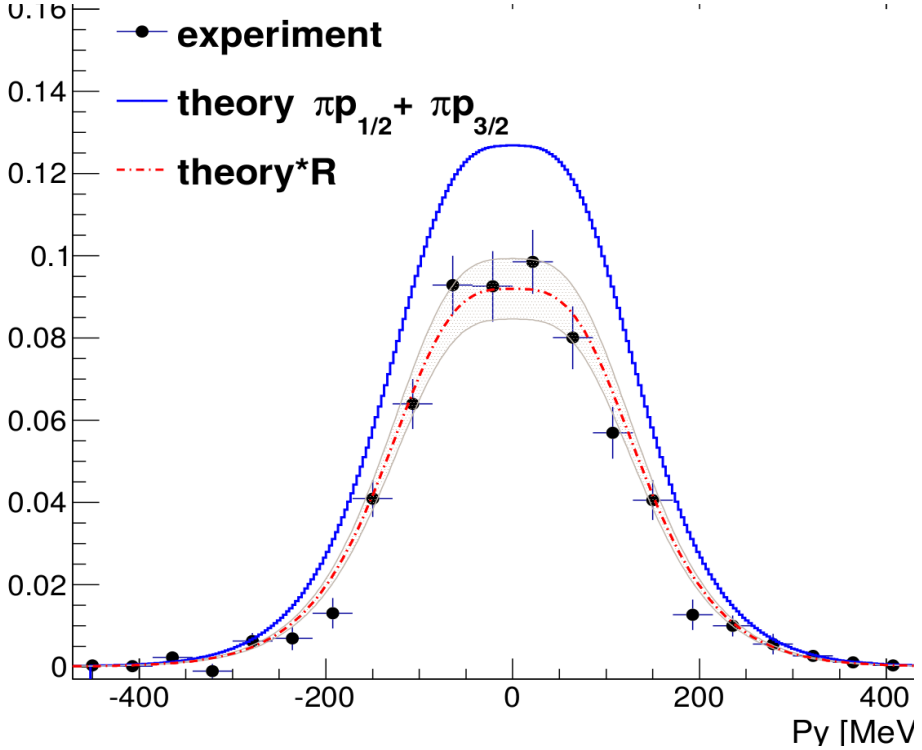
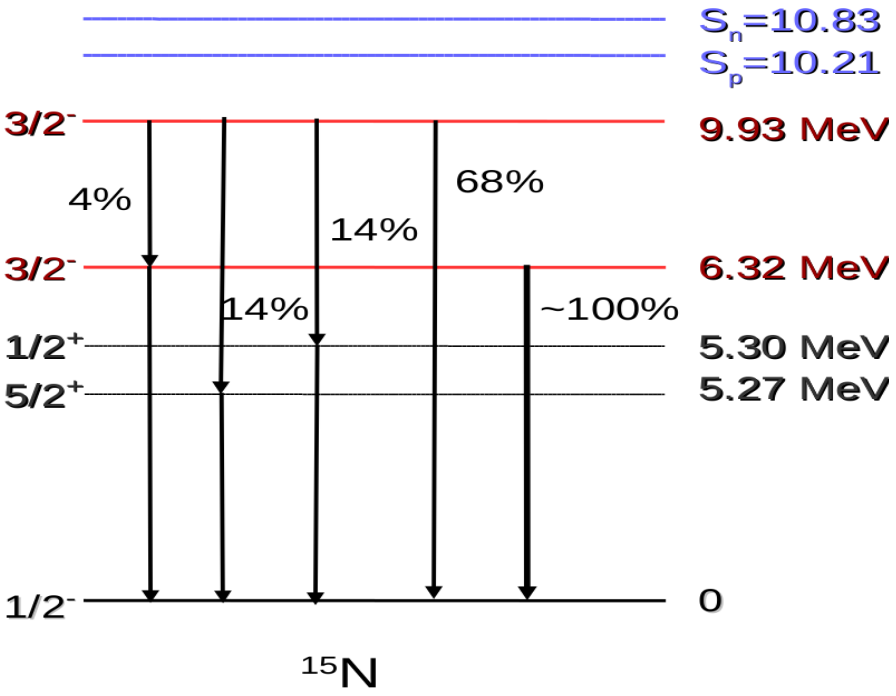


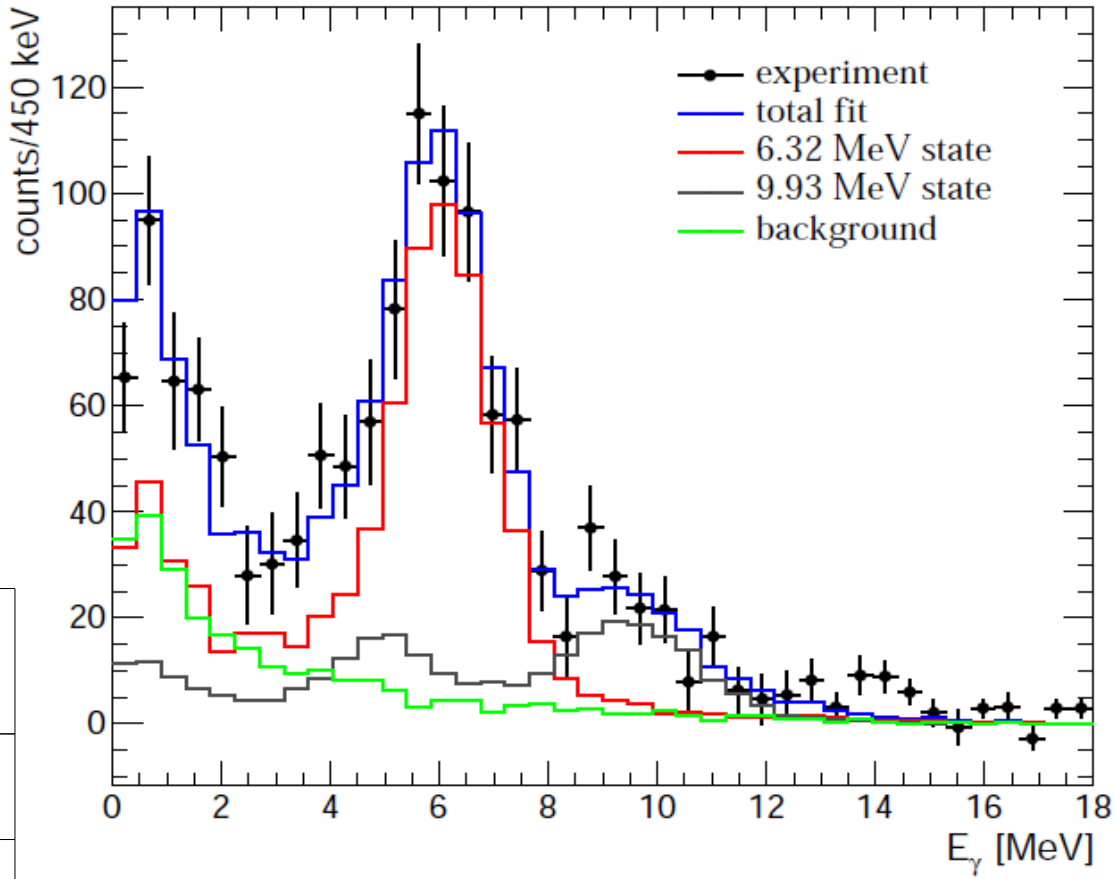
Inclusive P_y distribution for
$1p_{1/2}$ and $1p_{3/2}$ proton knockout

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



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)

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

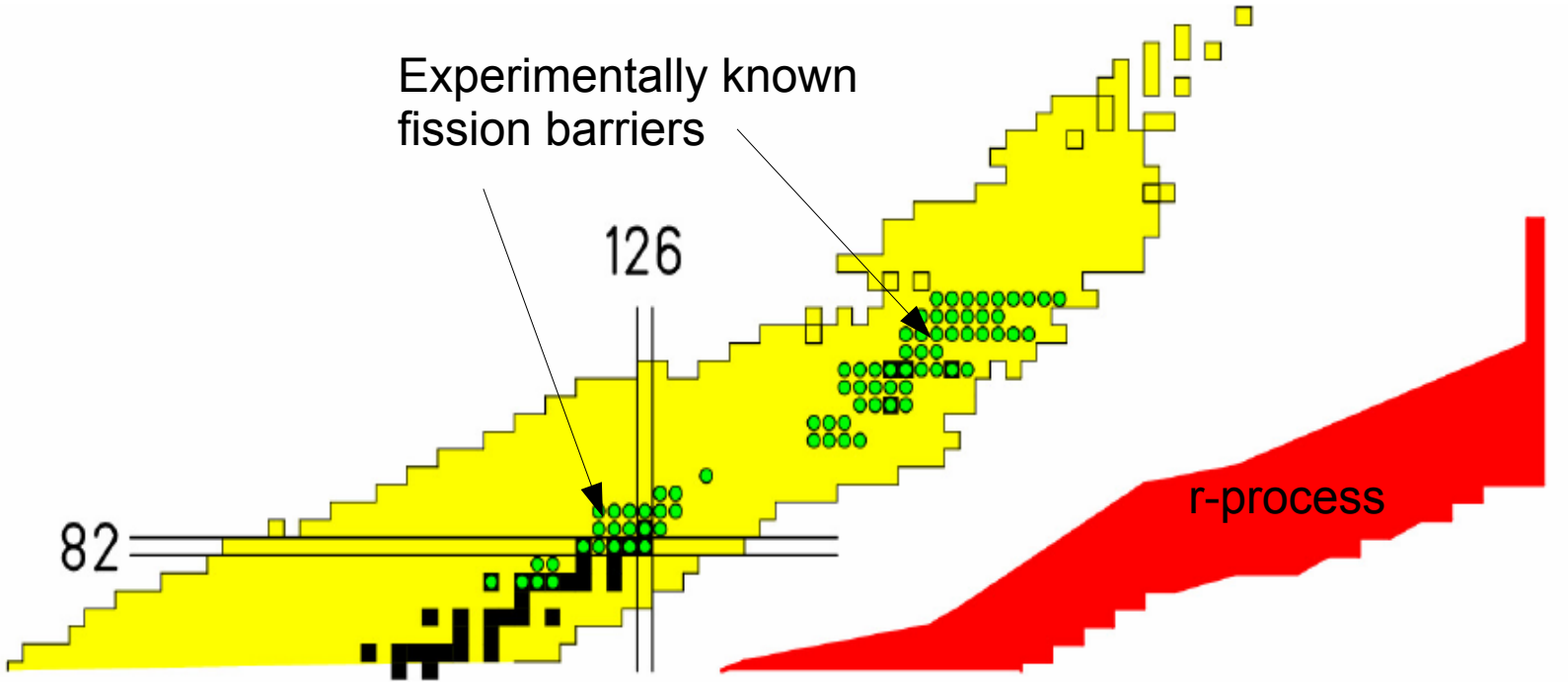


Spectroscopic factors deduced from the theoretical predictions and partial cross sections obtained from the fit of the γ-spectrum.

← (e,e'p) @ NIKHEF

Fission Reactions of Neutron-rich Nuclei via quasi-free (p,2p) Scattering

Why Fission Barrier Studies of n-rich Nuclei?

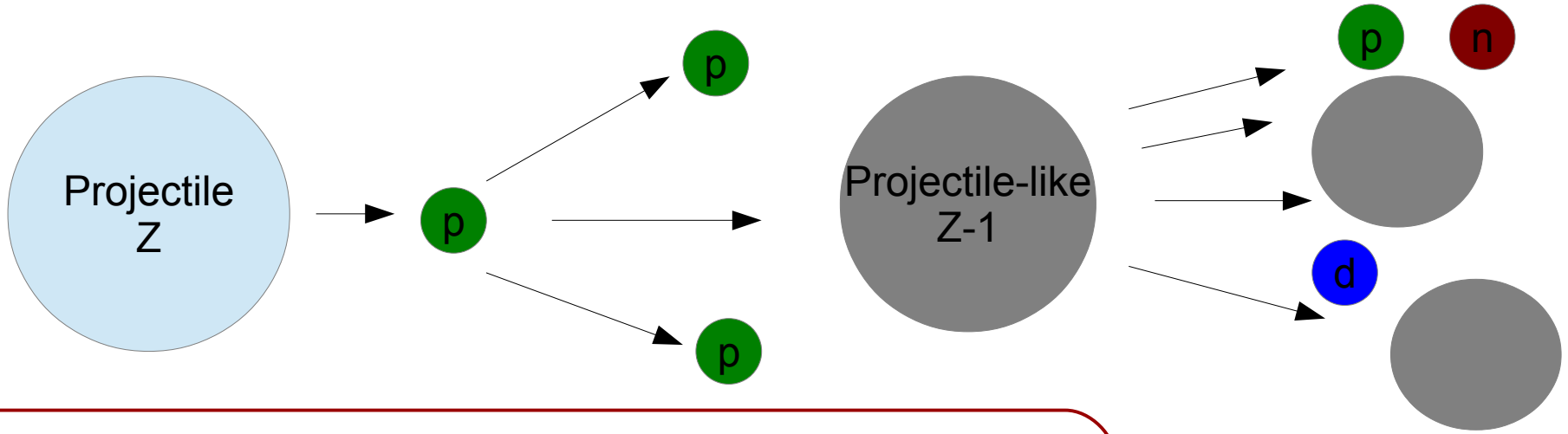


http://www-nds..iaea.org/RIPL-2

- Termination of r-process, which is very sensitive to the fission barrier
- Experimentally, fission barriers are known only around the stability line.
  → extrapolating of fission barriers in the theory
  → uncertainties in the theoretical parameters
  → discrepancies between different approaches

Why Fission Studies via Quasi-free (p,2p)

- Transfer reactions: thin d-target and low beam energy → low reaction rate & low excitation states & complex reaction → more background
- QF (p,2p): thick p-target and high beam energy → high reaction rate & high excitation states & clean reaction → less background



- These studies allow us to enhance our knowledge in

  - isospin dependence of fission barriers
  - fragment mass distribution (asymmetric vs symmetric)
  - recycling of the r-process

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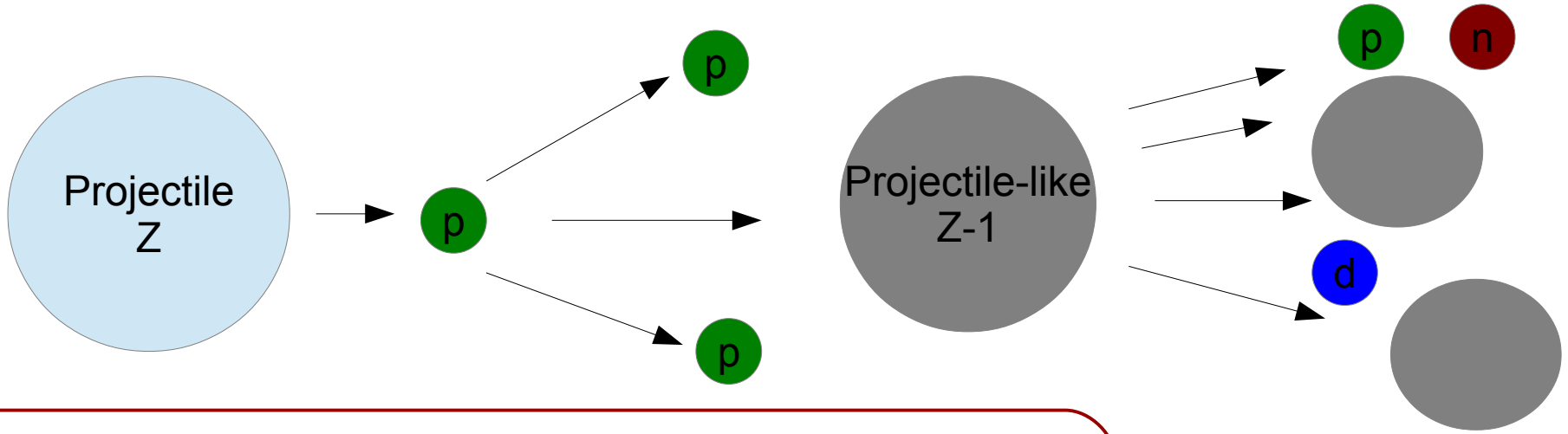

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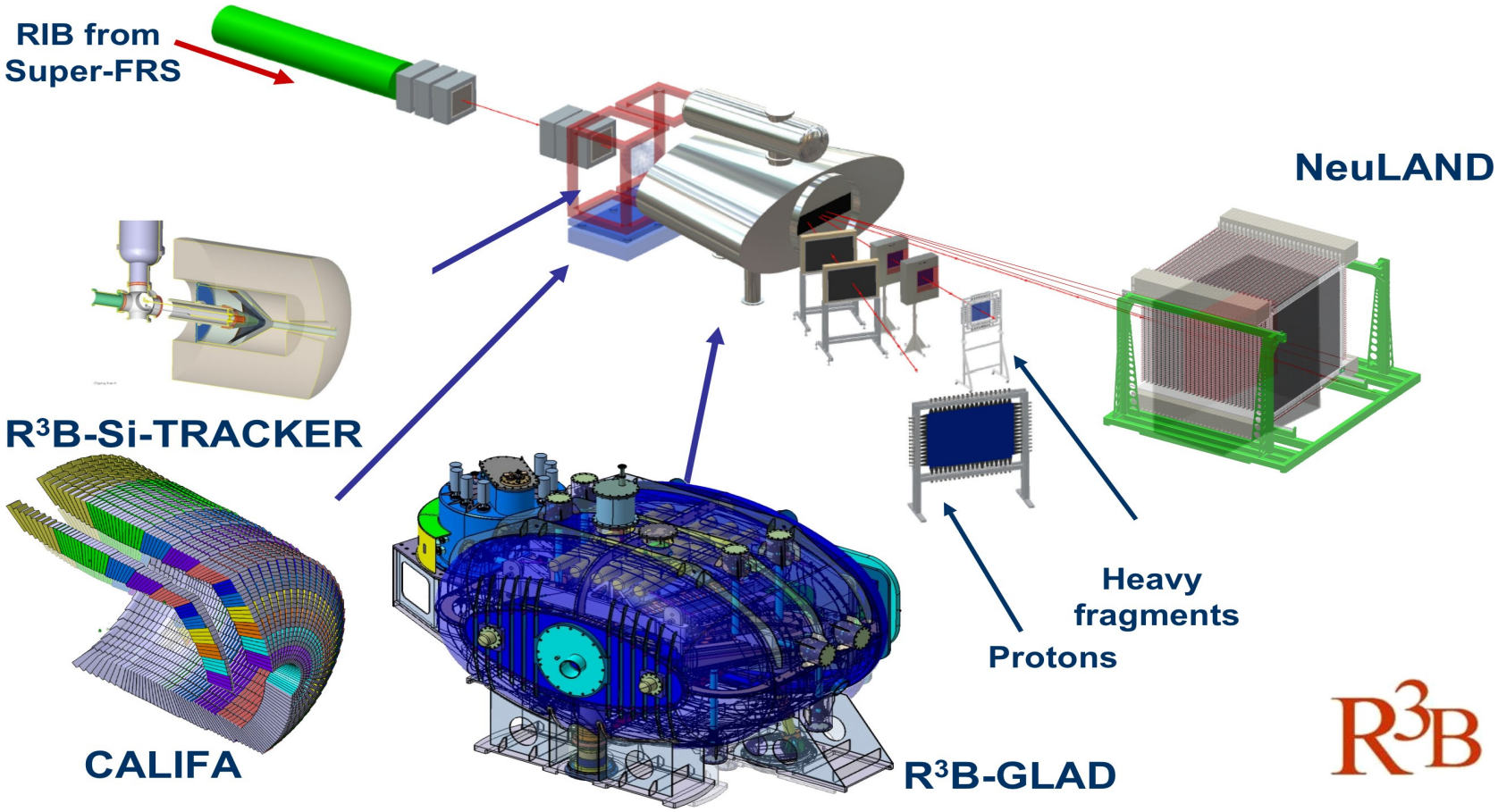
Summary

- Quasi-free knockout reactions in inverse kinematics provide a direct tool to obtain spectroscopic information.
- Inclusive cross sections were measured for the projectiles $^{13\text{-}18}$O and $^{21\text{-}23}$O.
- The reduction factor obtained from ^{16}O(p,2p)^{15}N reaction is in agreement with the results from the (e,e'p) reaction at NIKHEF facility.
- A weak or no dependence of single-particle strength on the isospin asymmetry has been observed.
- It is necessary to understand the reaction mechanism of knockout for deeply bound states at intermediate energies.
- Fission barrier height of n-rich nuclei plays an important role in the understanding of the r-process.
- The future R3B/FAIR setup offers an experimental accessibility to the r-process region.

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;