Experimental Results on QFS in inverse kinematics

Stefanos Paschalis

Technical University of Darmstadt

R^3B collaboration

Leyla Atar, Matthias Holl, Alina Movsesyan, Valerii Panin : Thanks for the slides!

March 2nd – 13th 2015, INT Workshop, Seattle, “Reactions and Structure of Exotic Nuclei”

Motivation

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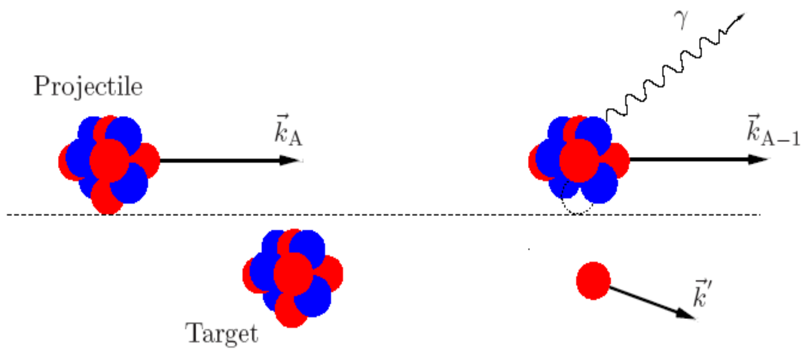
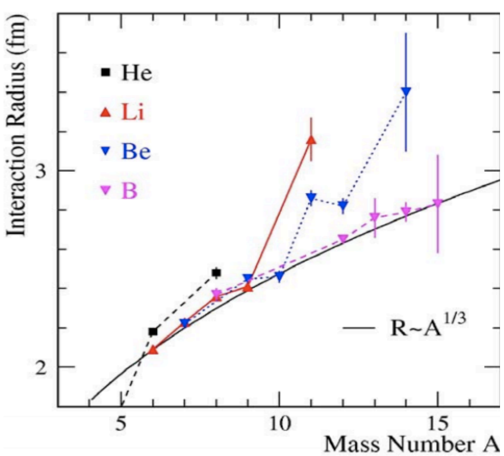
QFS in inverse kinematics as a tool to:

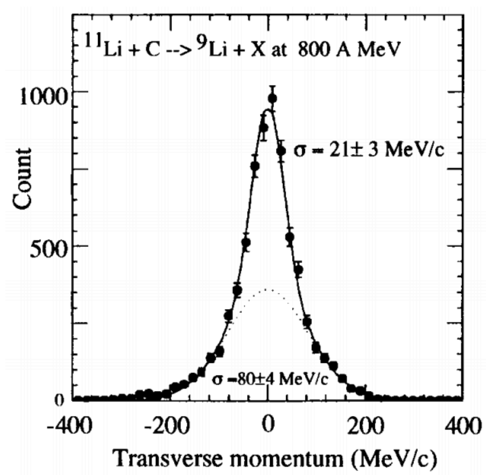
- perform spectroscopic studies of exotic nuclei
- populate systems beyond the neutron/proton driplines
- Study clustering in nuclei
- probe correlations (short range)

Knockout reactions: a tool to probe nuclei far from stability



Knockout reactions on light nuclear targets have helped to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion, halo nuclei…





Interaction cross section → Interaction radii

$$\sigma_{reac} = \pi\,(R_P + R_T)^2$$

$$R_X = r_0 A_X^{1/3}$$

I. Tanihata *et al.*, PRL 55 (1985) 2676, PLB 206 (1988) 592

Knockout reactions: a spectroscopic tool to study shell evolution far from stability

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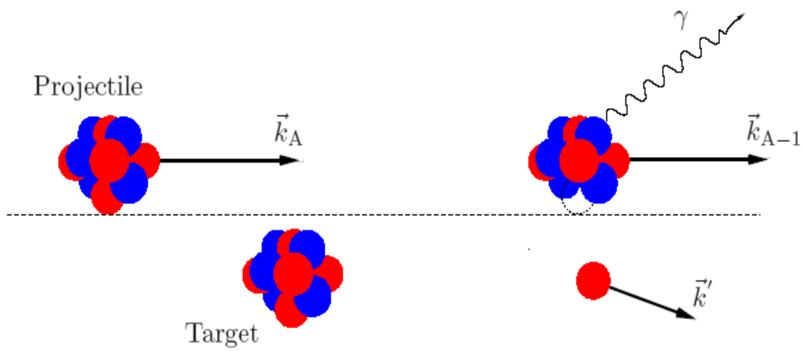
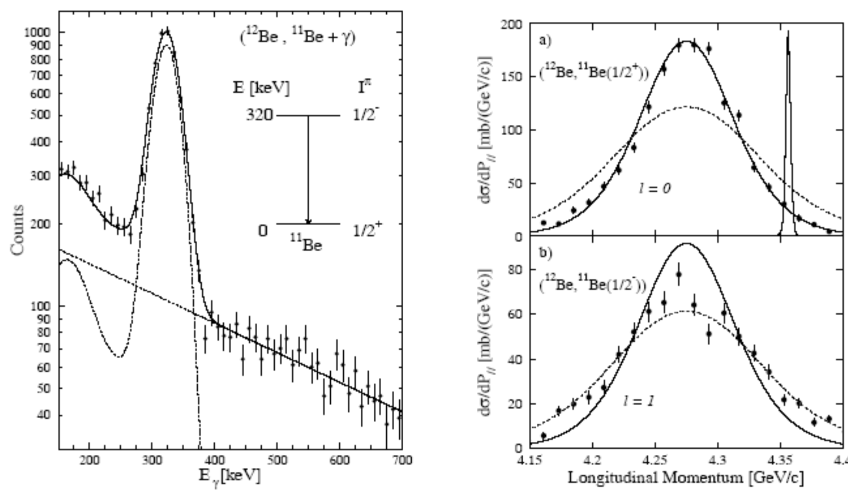


Knockout reactions on light nuclear targets have helped to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion, halo nuclei…

Navin, A. et al. PRL **85** (2000) 266



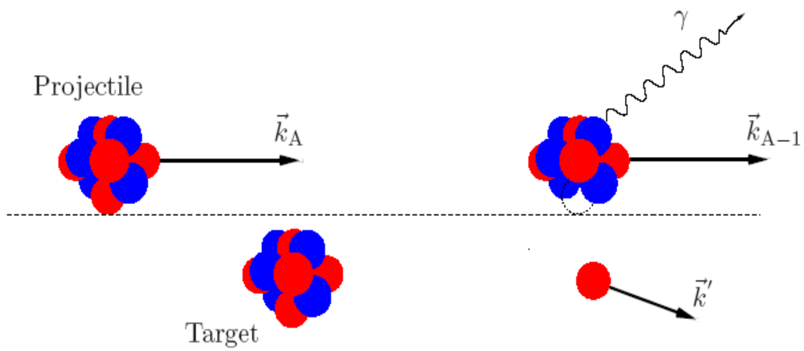
Spectrometer → momentum distributions and Mass ID

γ-ray detector → select final state

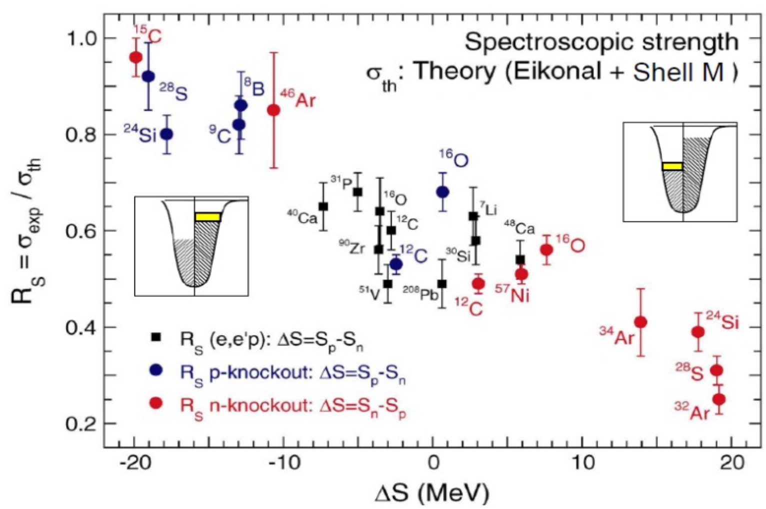
Momentum distributions → orb. ang. mom.

Partial cross sections → spectr. factors

Knockout reactions: a spectroscopic tool to study shell evolution far from stability



weakly bound strongly bound

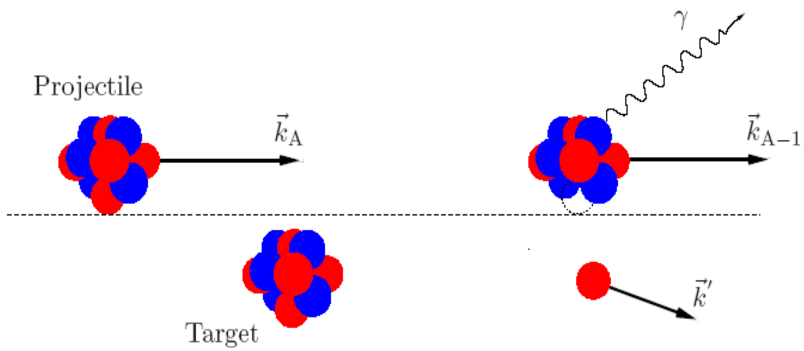


A. Gade, *et.al.* PRC 77, 044306 (2008)

Knockout reactions on light nuclear targets have helped to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion, halo nuclei…

Quenching of spectroscopic factors

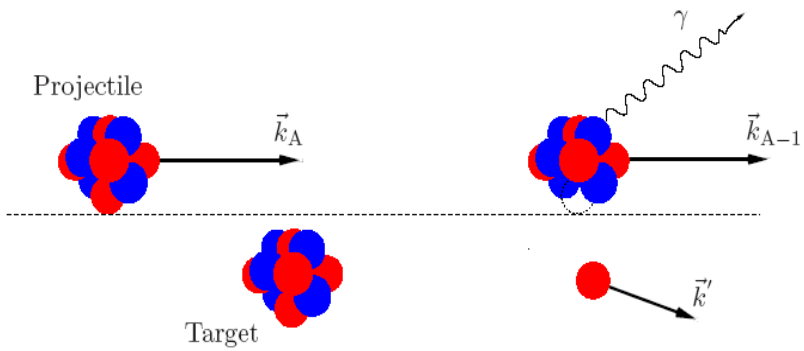
Complementary spectroscopic tools



Knockout reactions on light nuclear targets

Strong absorption → surface localized

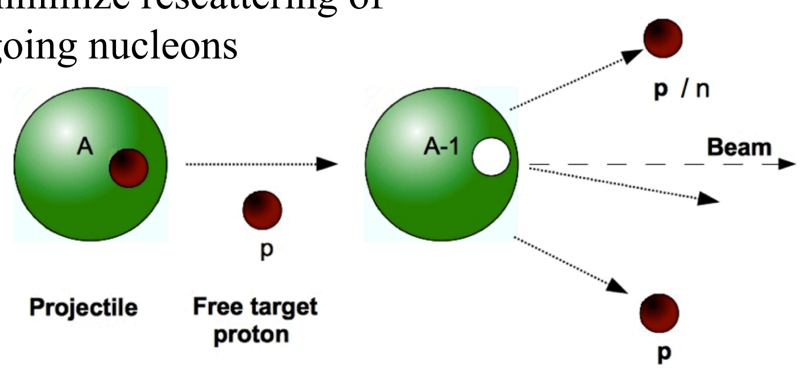
Complementary spectroscopic tools



Knockout reactions on light nuclear targets

Strong absorption → surface localized

few hundred MeV/nucleon to minimize rescattering of outgoing nucleons

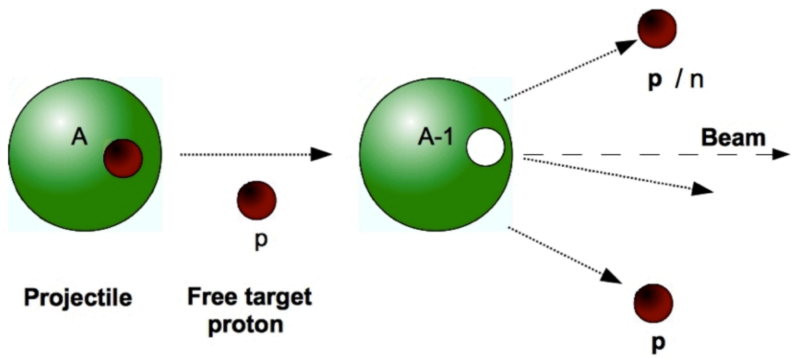


QFS reactions (p, 2p), (p, pn), (p, pα) etc. on a proton target in inverse kinematics

Weaker absorption → probing inner shells

- Evolution of shell structure
- Nucleon-Nucleon correlations (short-range, tensor, …)
- Cluster structure
- States beyond the neutron dripline

Quasi-free scattering



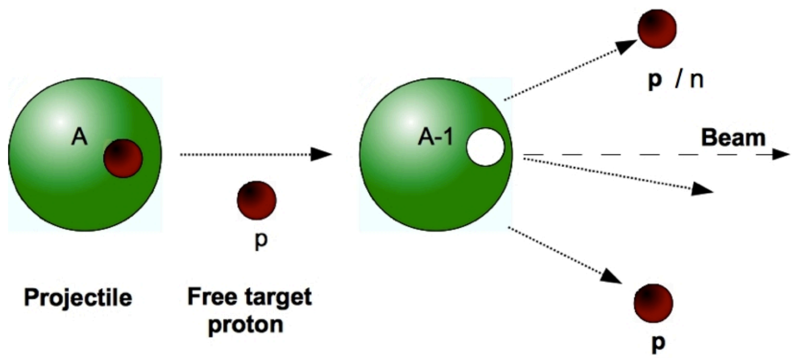
QFS reactions

Spectrometer → momentum distributions and Mass ID

γ-ray detector → select final state

Target recoil detector → detect scattered nucleons

Quasi-free scattering



QFS reactions

Spectrometer → momentum distributions and Mass ID

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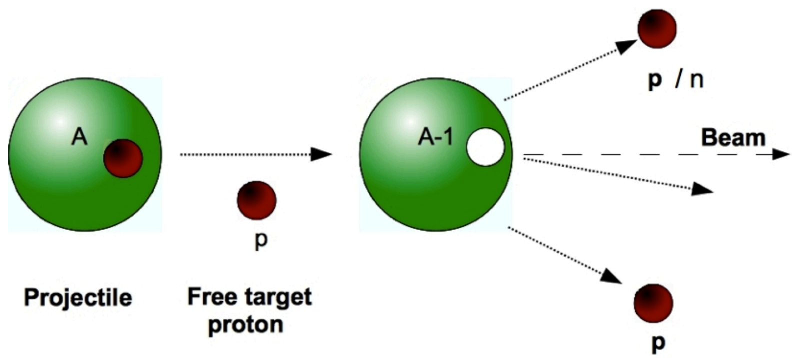
Target recoil detector → detect scattered nucleons

Scattered nucleons → complete and redundant kinematical measurement

Quasi-free scattering



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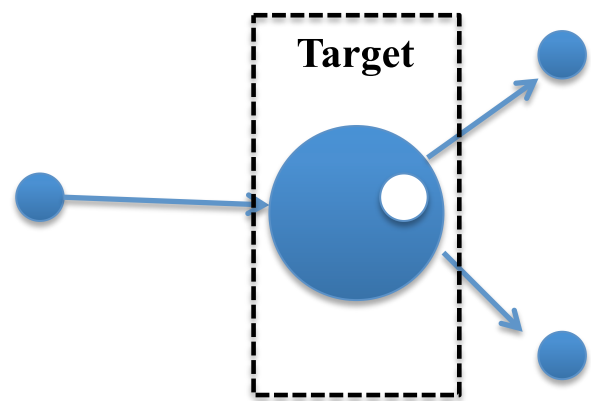
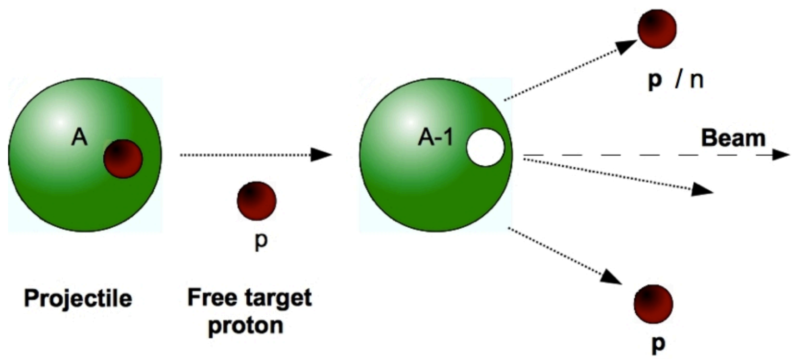
p,2p in normal kinematics



Quasi-free scattering



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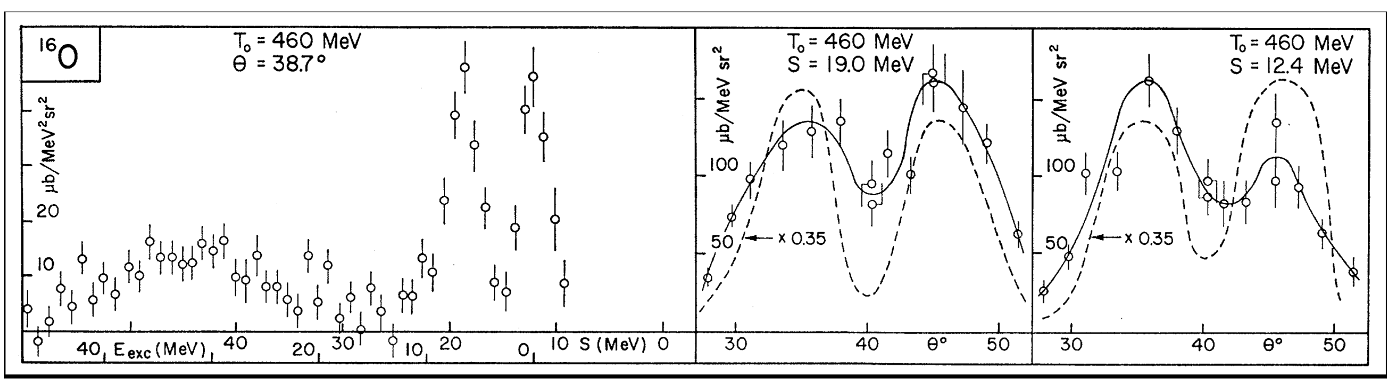
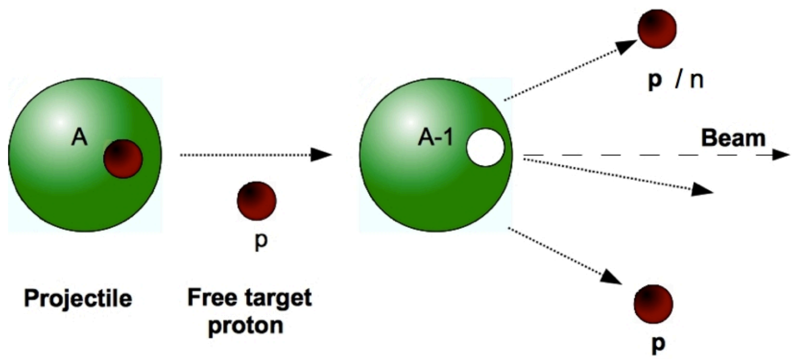


^{16}O (p,2p) in normal kinematics
G. Jacob et al., RMP 1966 38 121
PLB 45 (1973) 181

Quasi-free scattering



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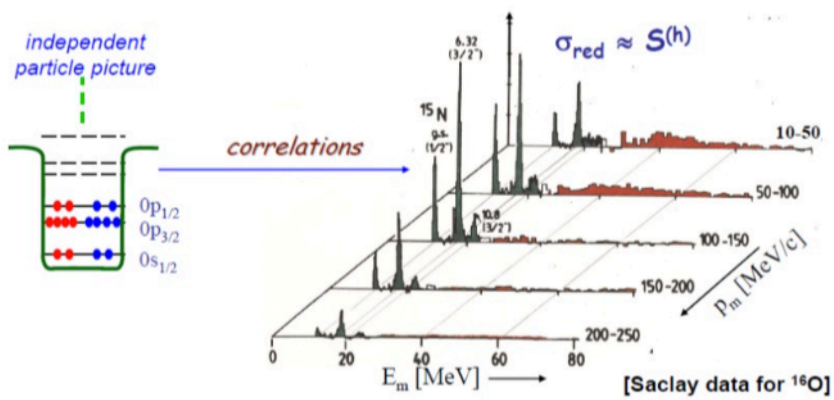

Minimizing FSI at larger momentum transfer

^{16}O (e,e'p)
Saclay data

QFS calculations by C. A. Bertulani

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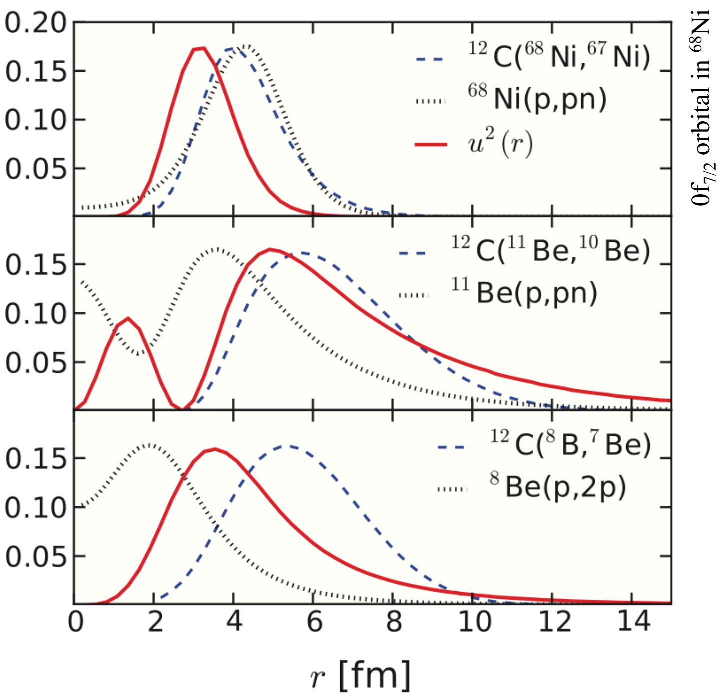
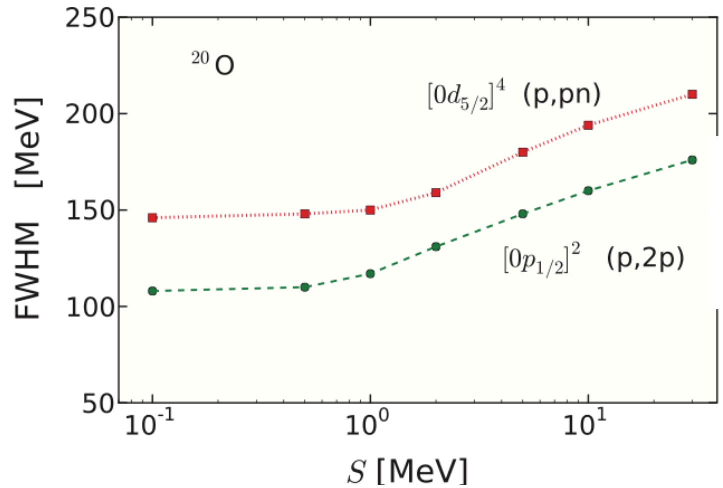
T. Aumann, C. A. Bertulani, J. Ryckebusch

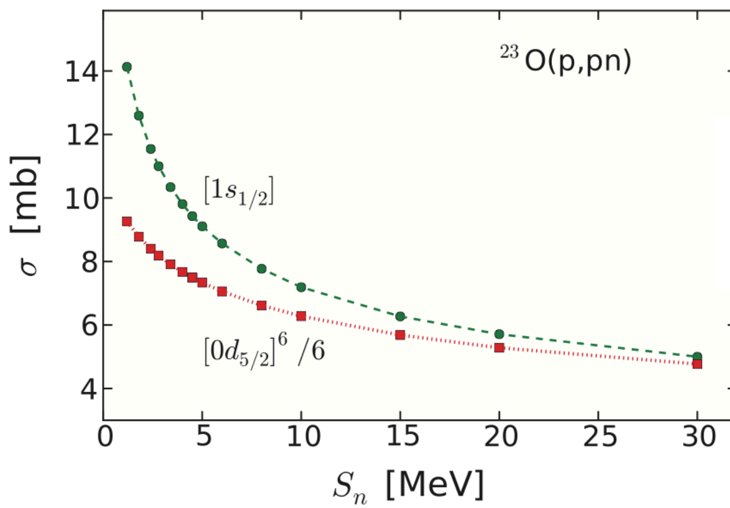
PRC 88, 064610 (2013)

Removal probability:
proton target compared to C target





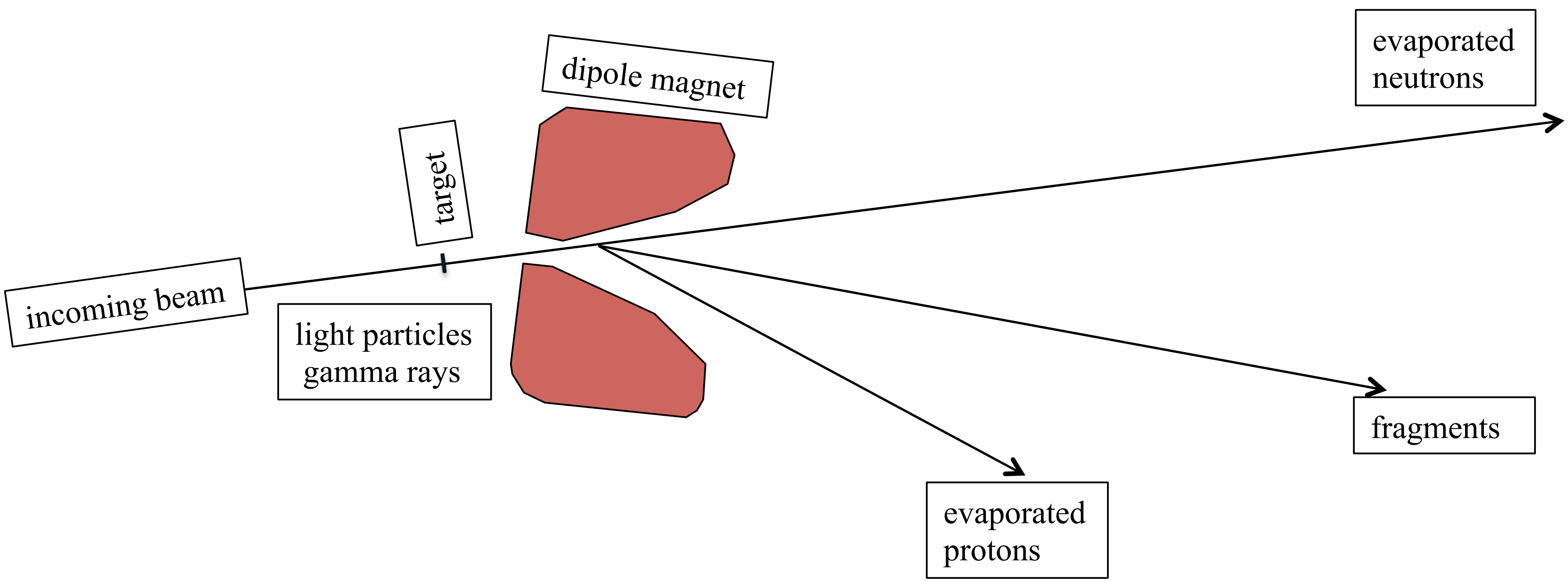
Momentum width dependence on separation energy



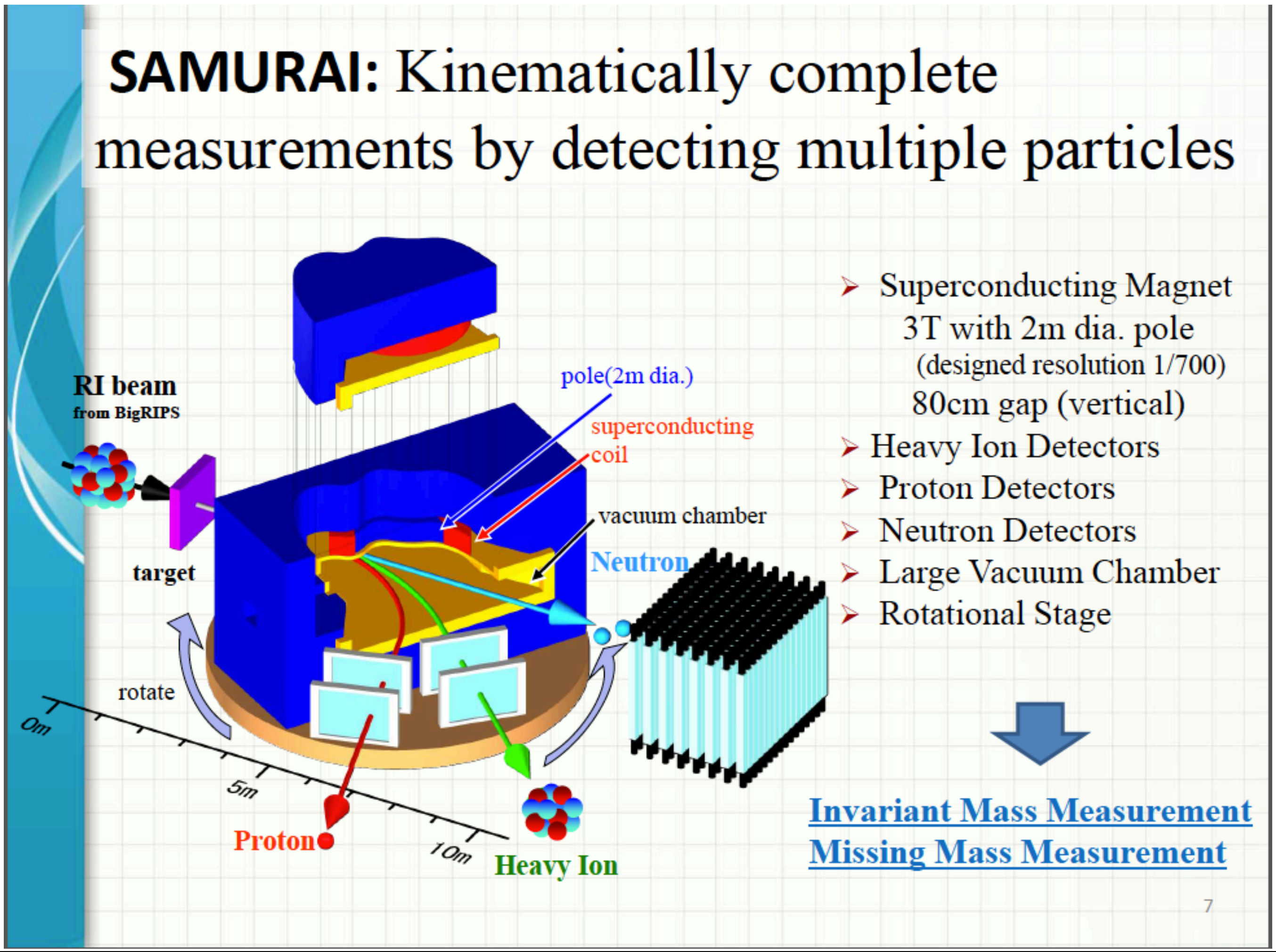
Cross section dependence on separation energy

Experimental setup for QFS

hundreds of MeV/nucleon incoming beam



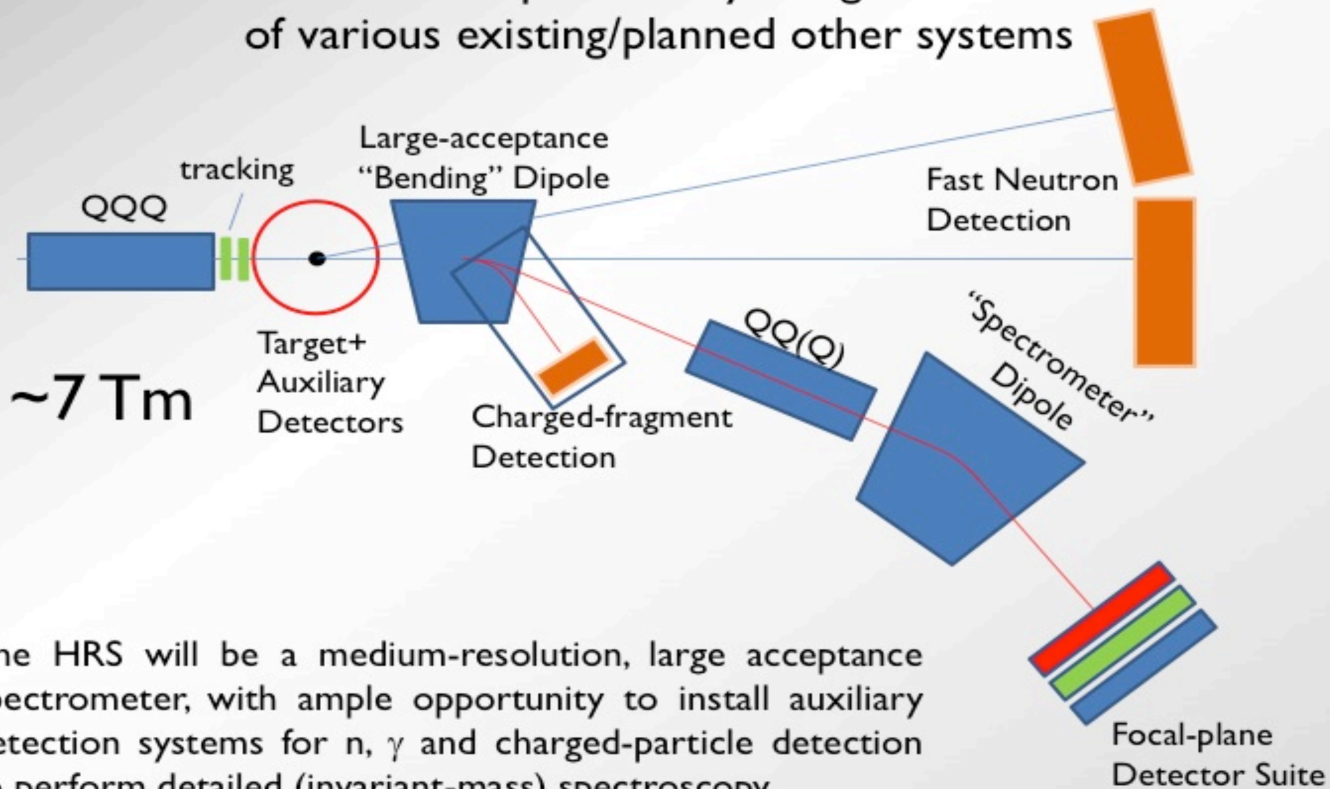
Experimental setup – SAMURAI @ RIBF



Slide from:
TadaAki Isobe

Experimental setup – HRS @ FRIB

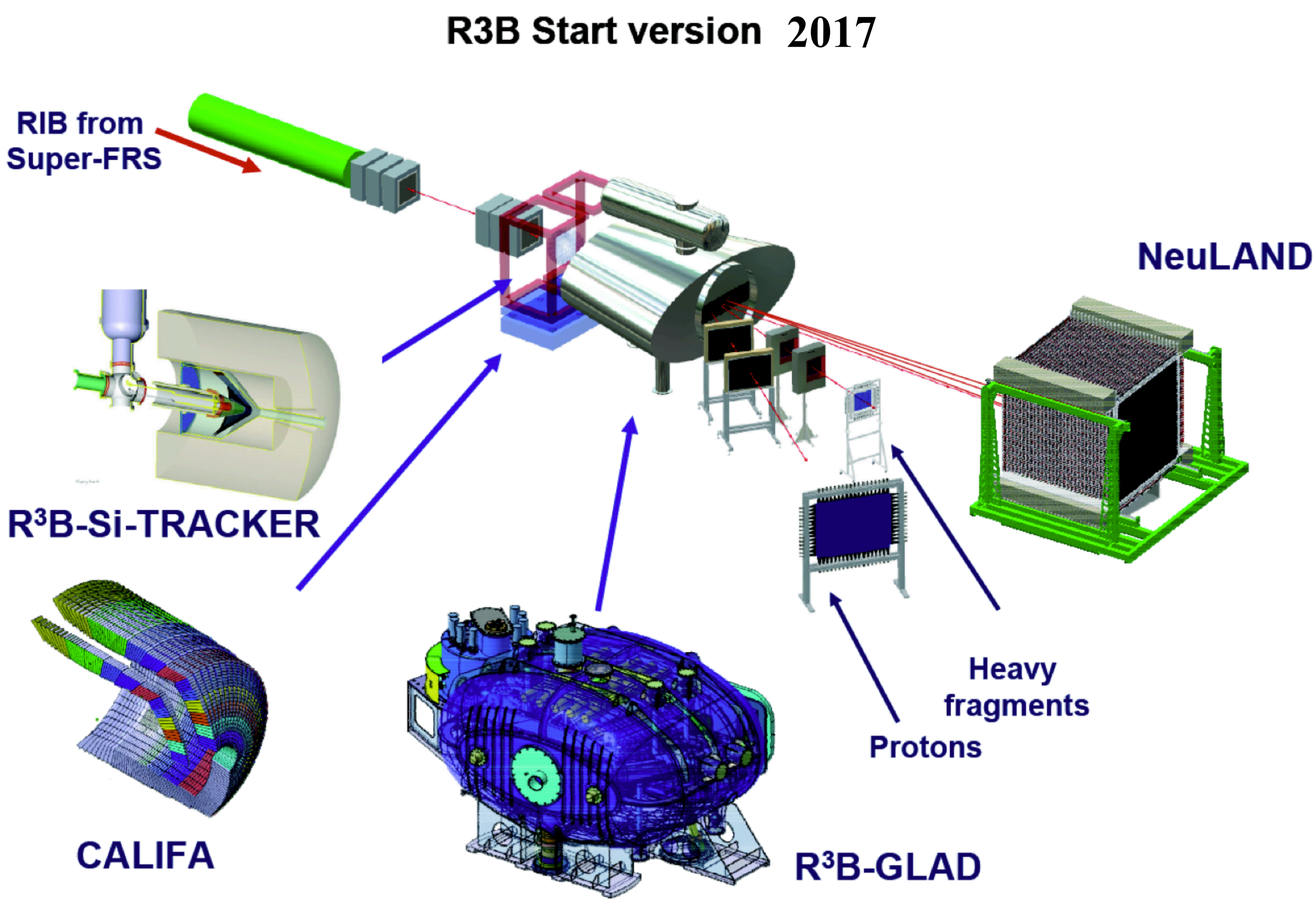
A very schematic layout discussed in the breakout session, evolved from an earlier preliminary design and considerations of various existing/planned other systems



The HRS will be a medium-resolution, large acceptance spectrometer, with ample opportunity to install auxiliary detection systems for n, γ and charged-particle detection to perform detailed (invariant-mass) spectroscopy.

Slide from:
M. Thoennessen

Experimental setup – R³B @ GSI/FAIR



Target recoil detection setup

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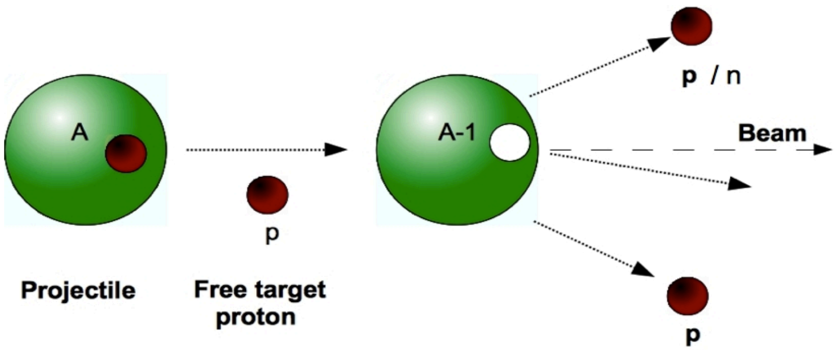
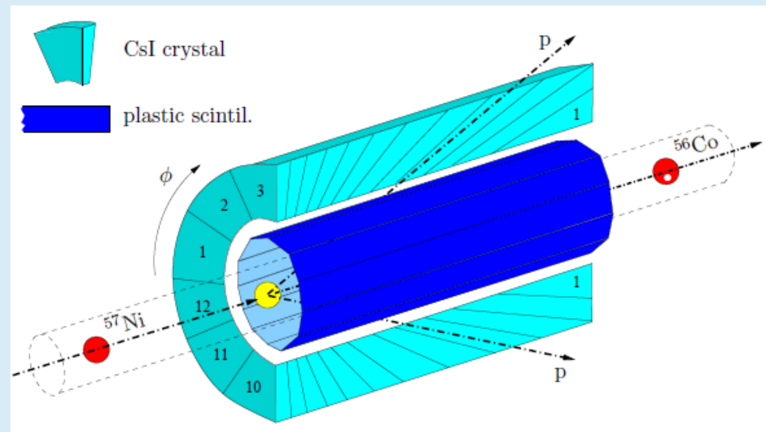
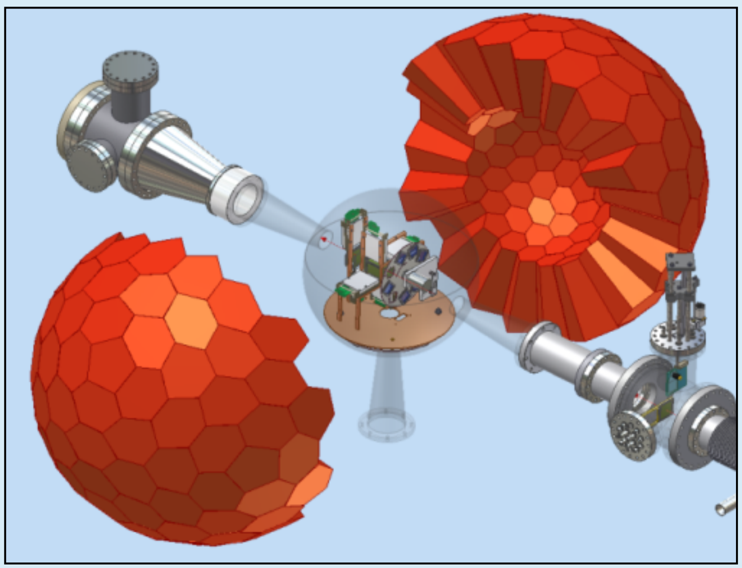


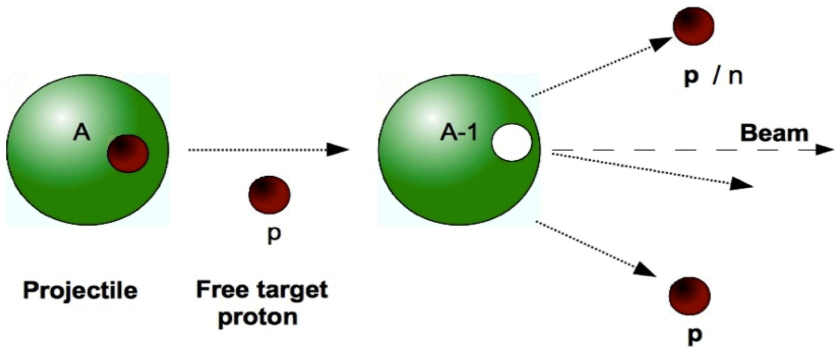
2005

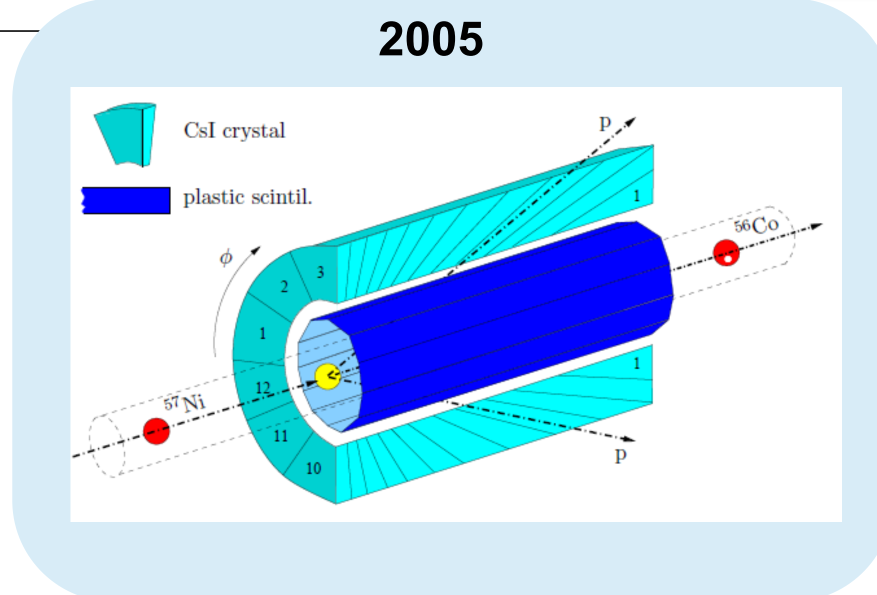


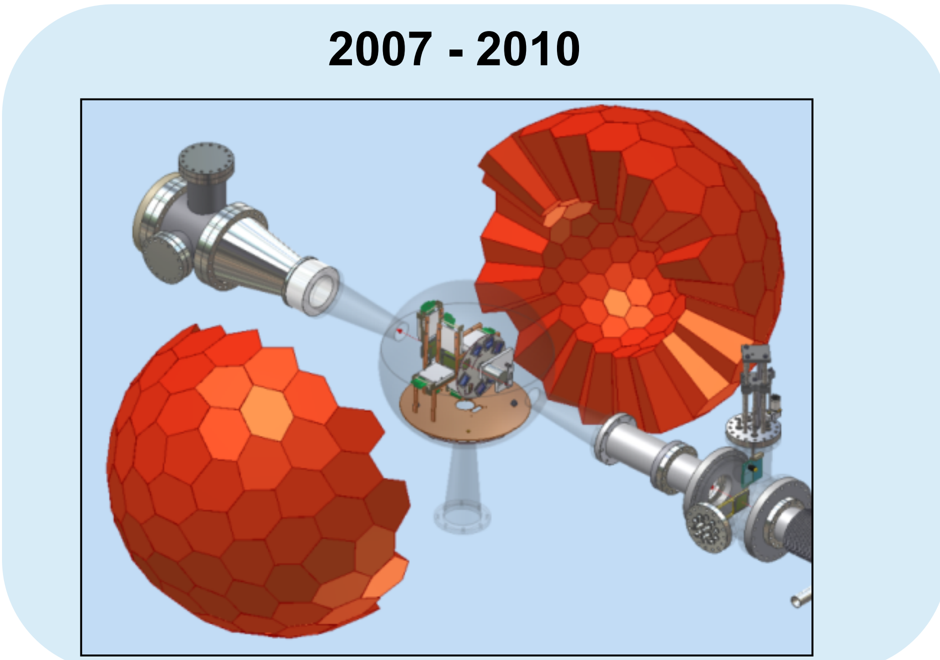
2007 - 2010



Target recoil detection setup

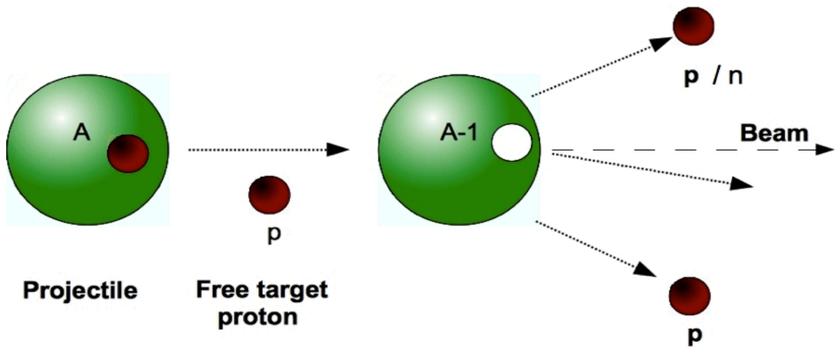




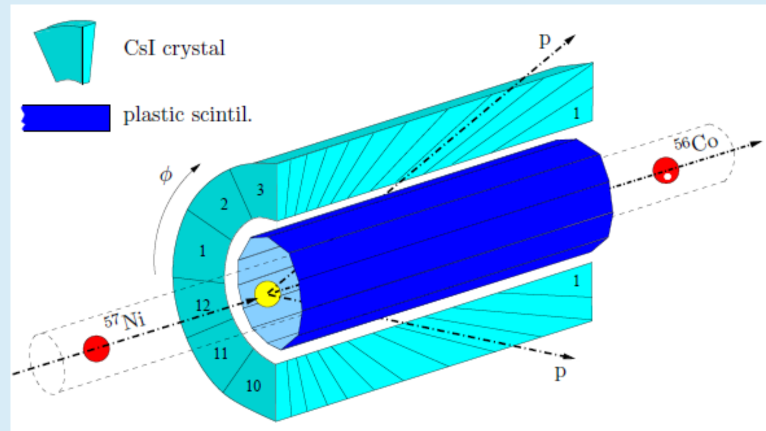


These setups provided good coverage but not good total energy measurement

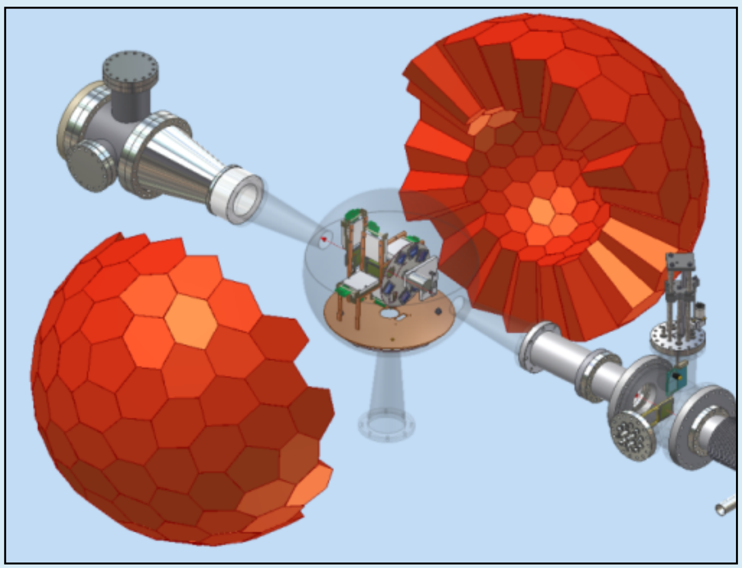
Target recoil detection setup



2005

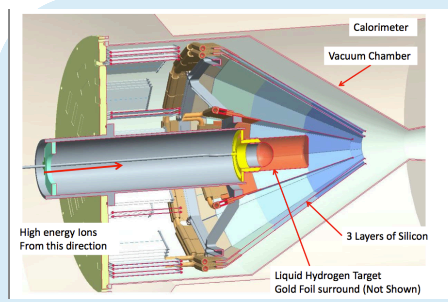


2007 - 2010

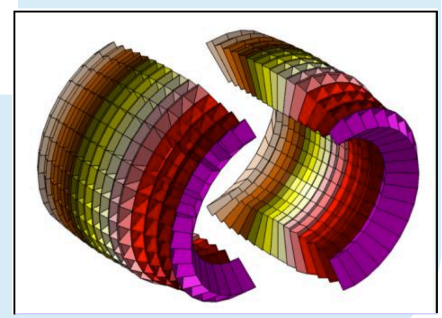


Future setup

CALIFA



Si Tracker



Rich physics cases in available (p,2p and p,pn) QFS data sets obtained with R^3B @ GSI

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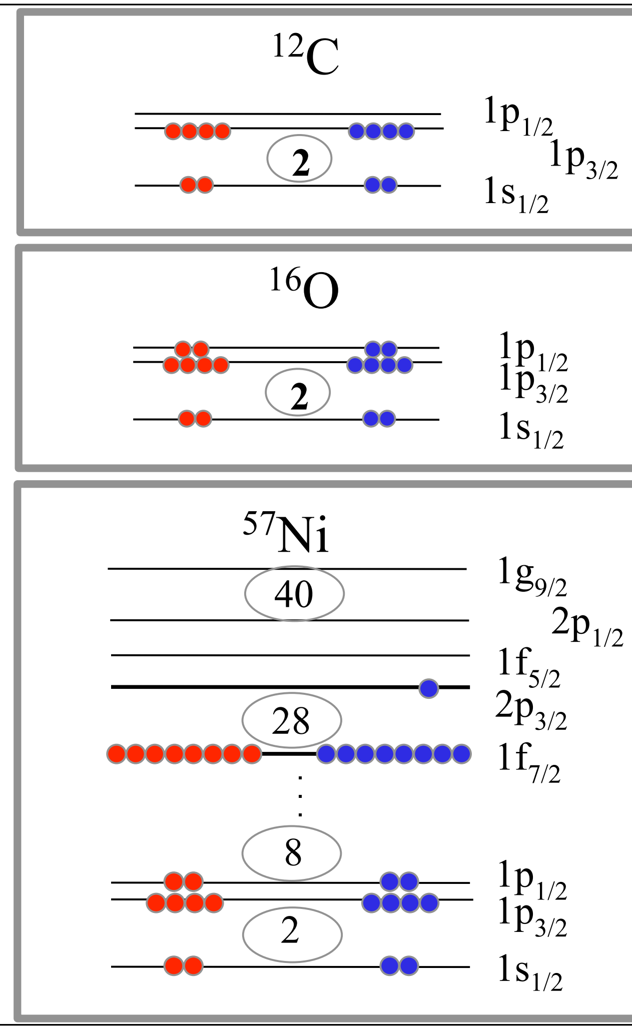
- **^{12}C isotope:** benchmark case
- **C isotopic chain :** Z = 6; N = 3 – 14
- **O isotopic chain :** Z = 8; N = 8 – 15
- **Ni isotopic chain :** Z = 28; N = 28 – 30, 39 – 44



Rich physics cases in available (p,2p and p,pn) QFS data sets obtained with R^3B @ GSI

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^{12}**C isotope:** benchmark case

C isotopic chain :

- known up to the drip lines
- accessible to ab-initio theories

…..

O isotopic chain :

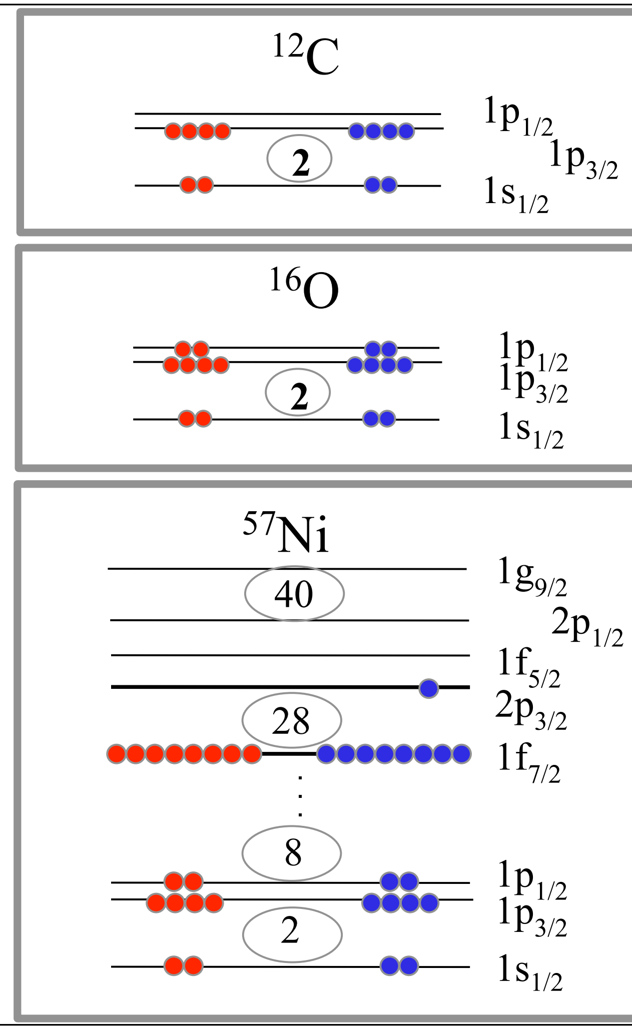
- "unexpected" end of drip line

…..

Ni isotopic chain :

- How magic is ^{68}Ni? – N=40 sub-shell closure
- Close to the "New" island of inversion (^{64}Cr, ^{66}Fe)
- Shell evolution towards ^{78}Ni

…..



Rich physics cases in available (p,2p and p,pn) QFS data sets obtained with R^3B @ GSI

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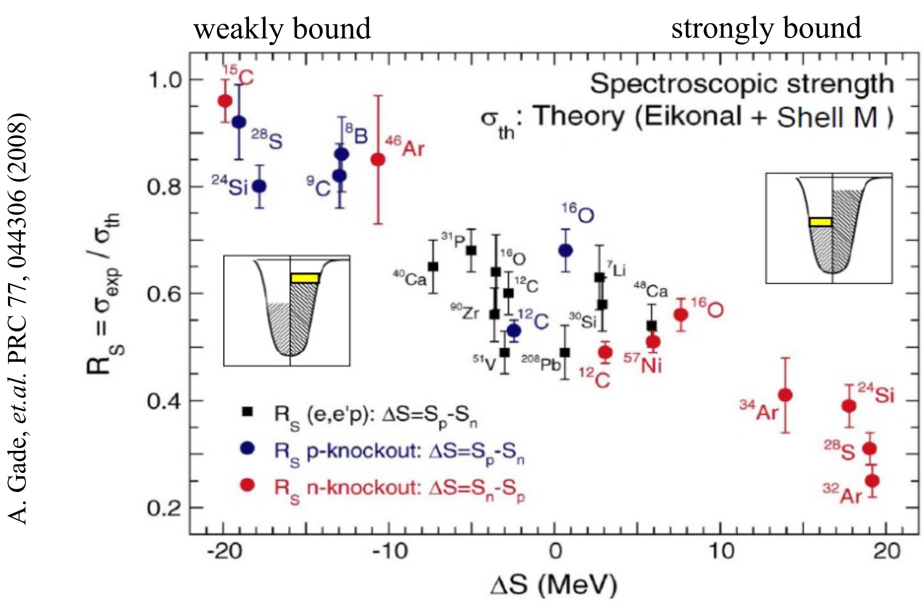
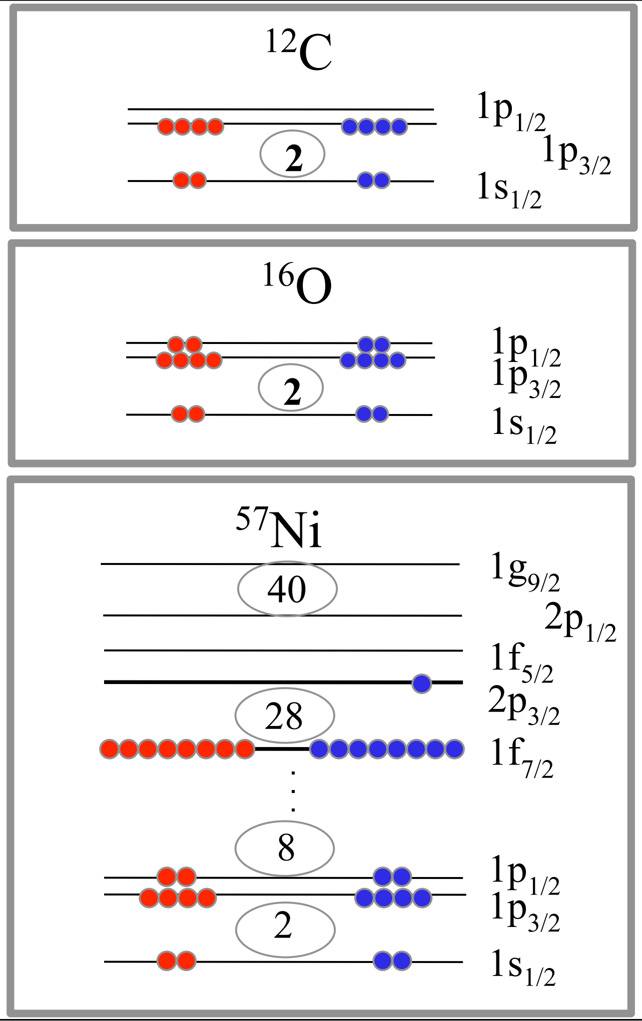
large range of separation energies and more sensitive to deeply bound states → independent and consistent measurement of reduction factors





$^{12}C(p,2p)$: QFS in inverse kinematics: a Benchmark experiment

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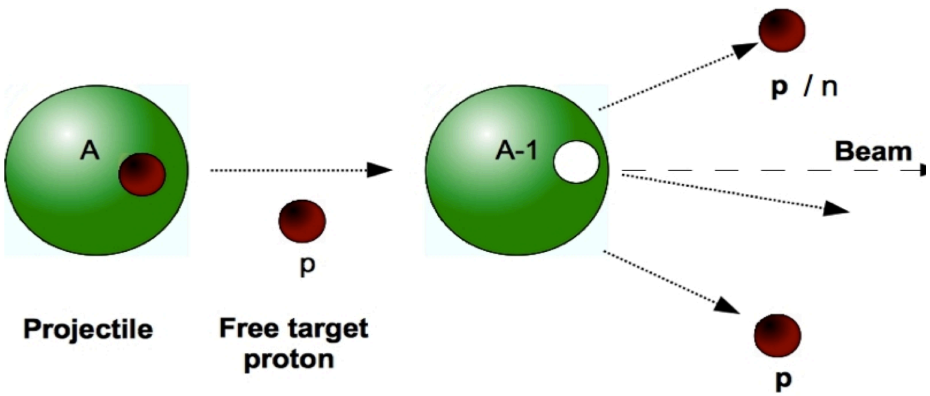
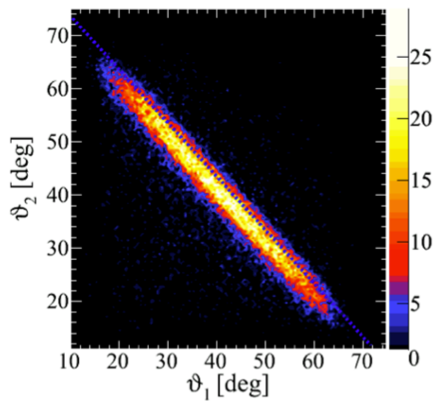
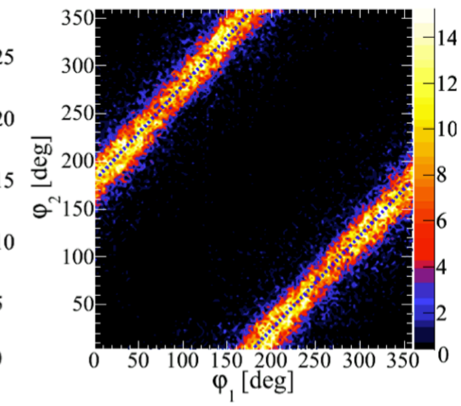
Strong angular correlations of the two protons







Analysis by V. Panin

^{12}C(p,2p): QFS in inverse kinematics: a Benchmark experiment

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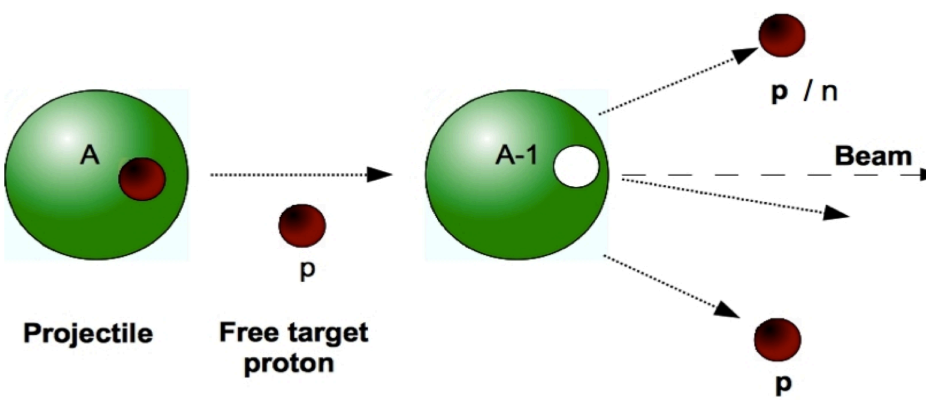

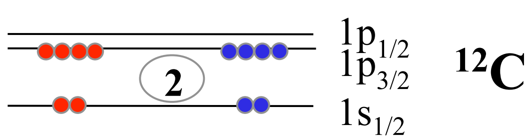

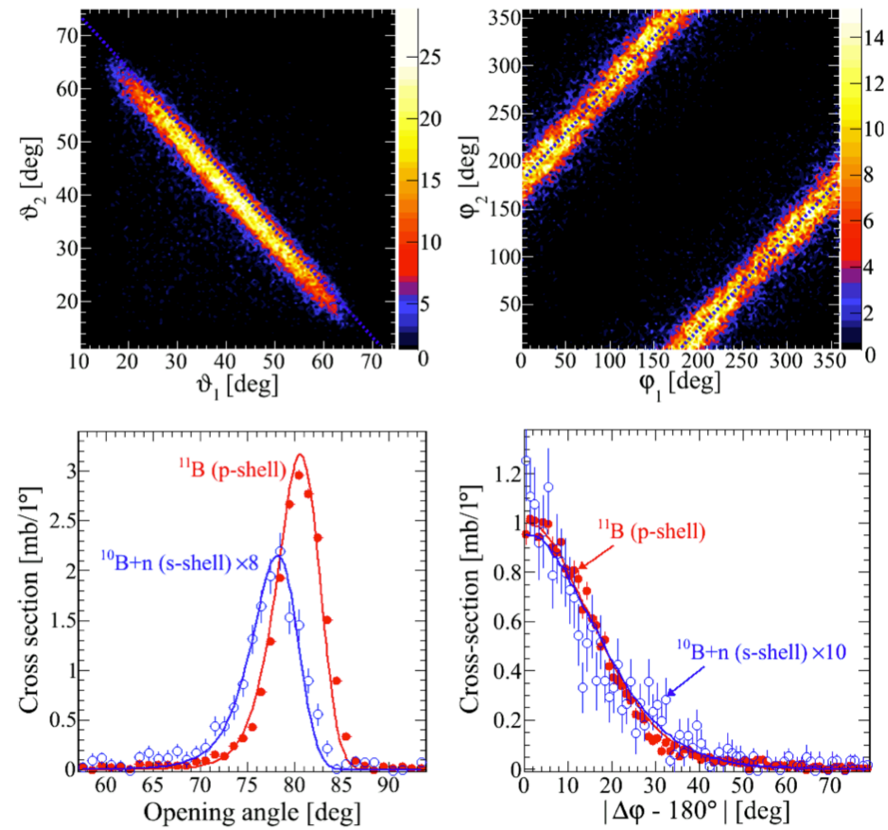

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$^{12}C(p,2p)$: QFS in inverse kinematics: a Benchmark experiment

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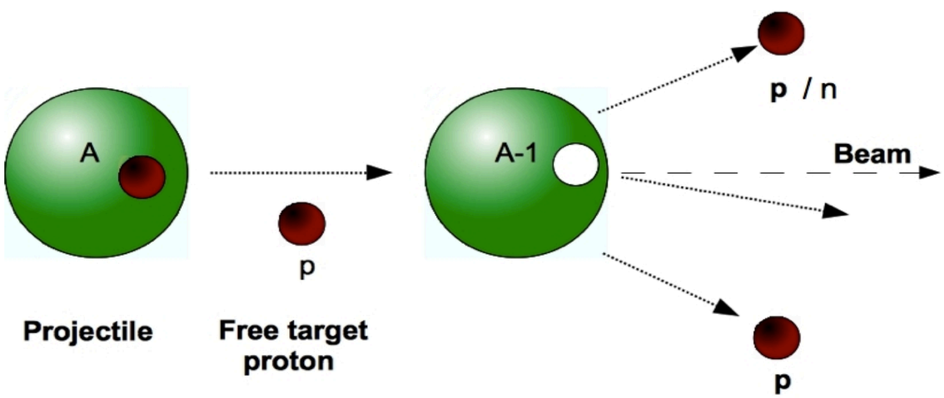
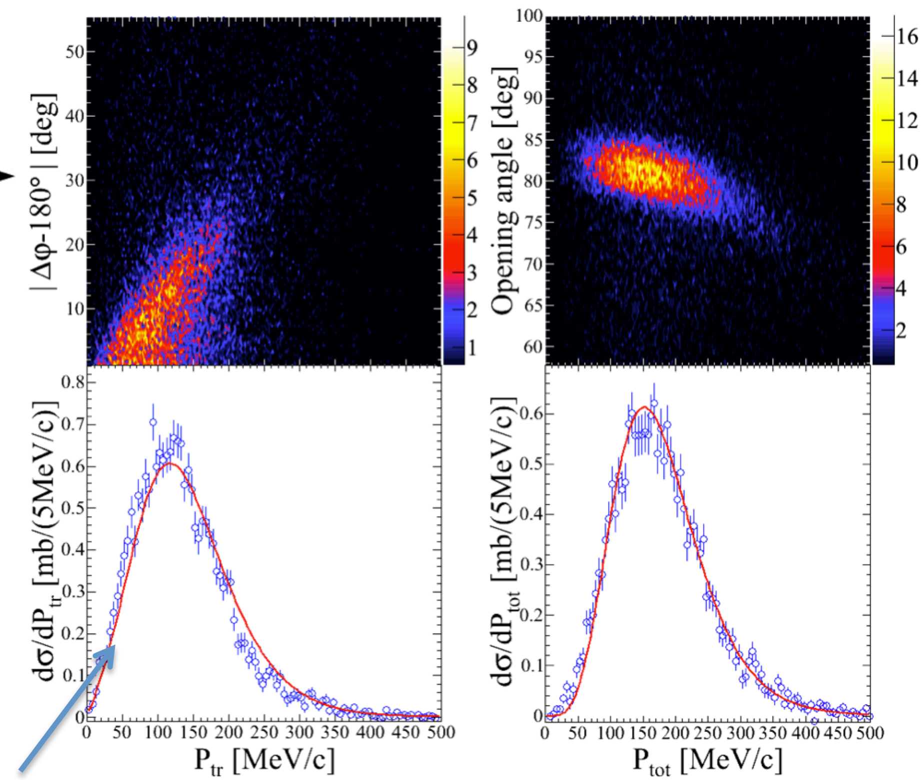
Kinematics are particularly important!





reaction theory
by C.A. Bertulani

Analysis by V. Panin

$^{12}C(p,2p)$: QFS in inverse kinematics: a Benchmark experiment

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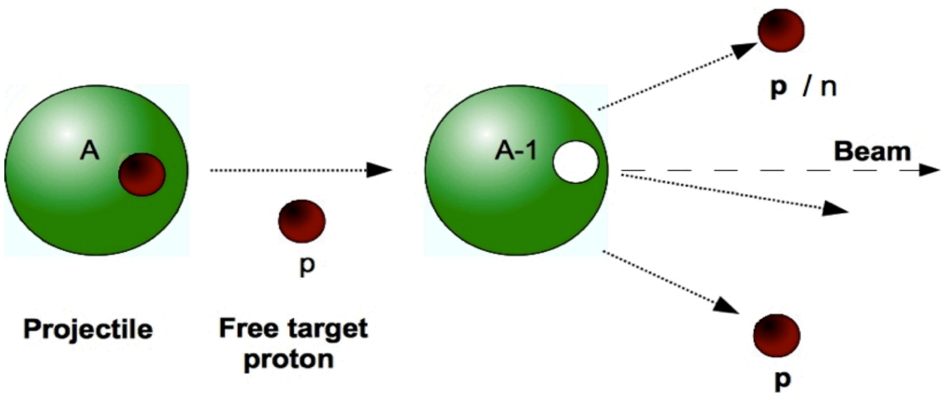

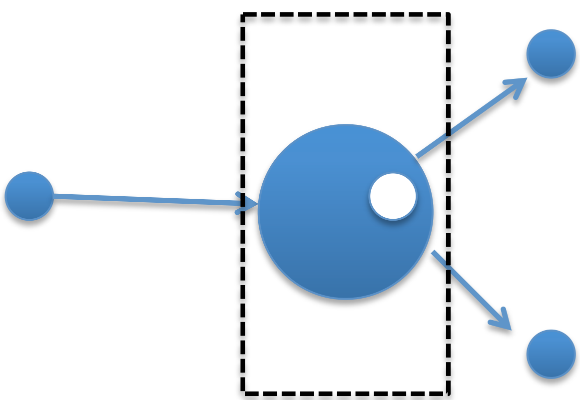

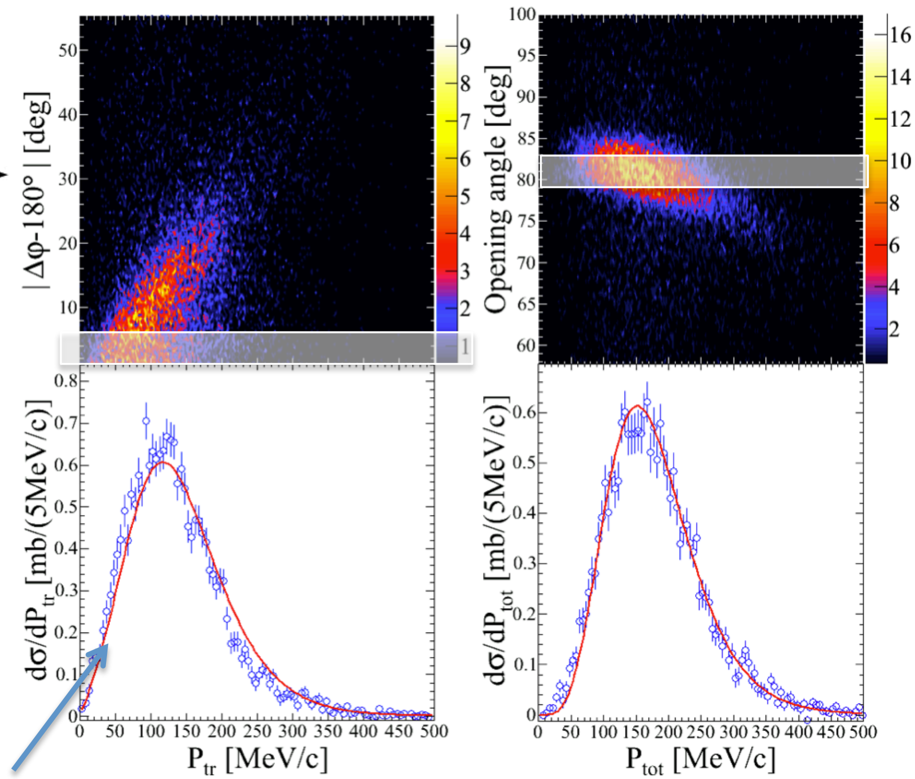

Analysis by V. Panin

reaction theory by C.A. Bertulani

$^{12}C(p,2p)^{11}B$

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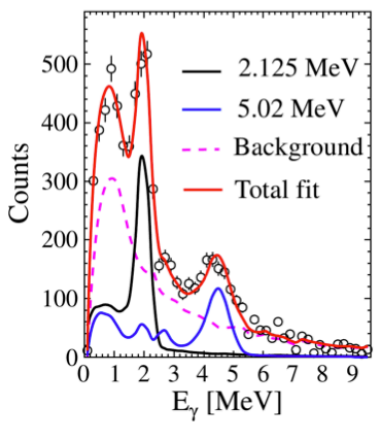
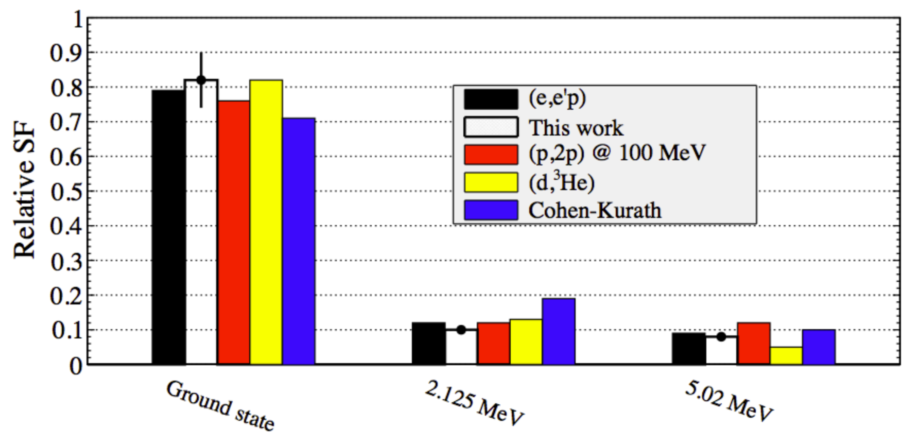
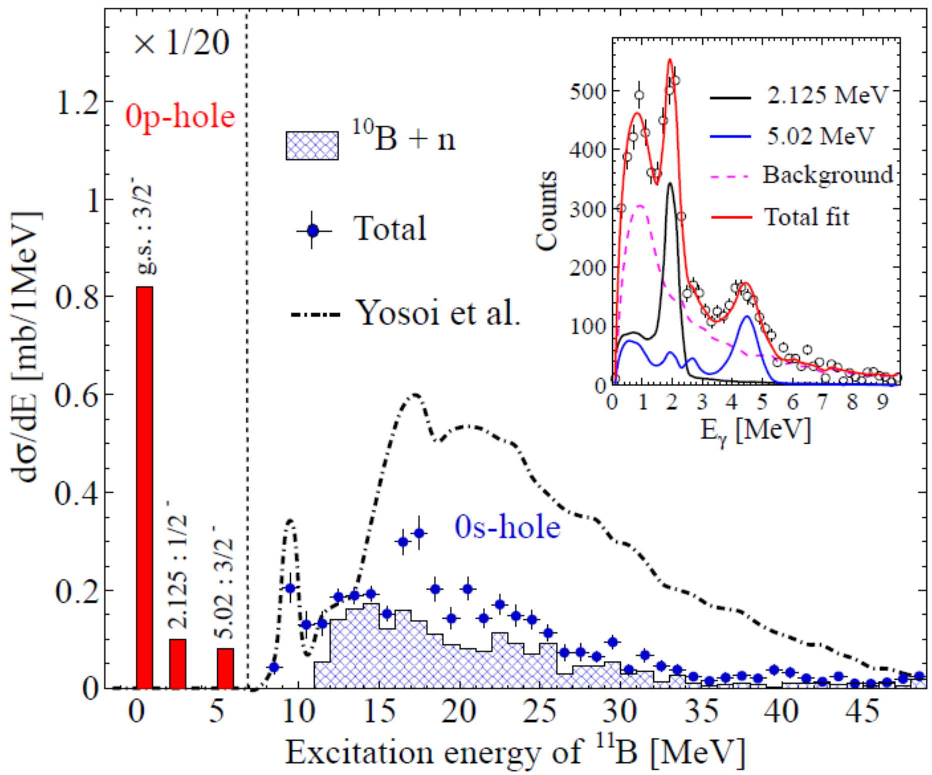
Spectroscopy of $0p$-hole residual states in ^{11}B from $^{12}C(p,2p)^{11}B$ reaction

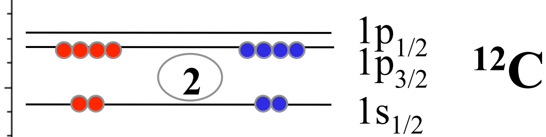
via Doppler-corrected γ-spectrum in coincidence with outgoing (bound) ^{11}B

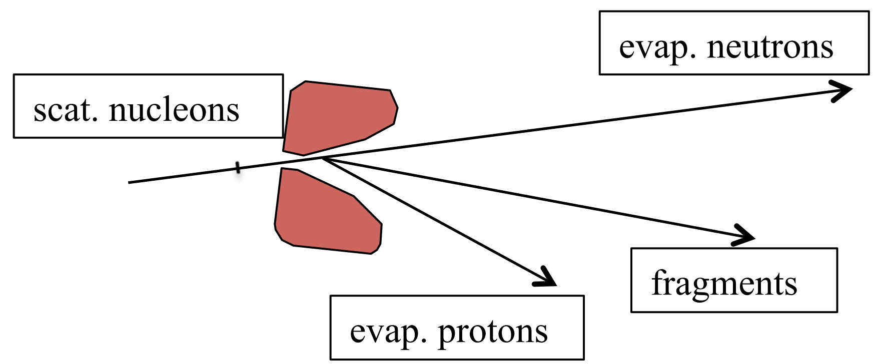




$^{12}C(p,2p)^{11}B^* \rightarrow (^{10}B + n), (^{10}Be + p), (^{7}Li + ^{4}He), ...$







Analysis by V. Panin

^{11}C(p,2p)^{10}B

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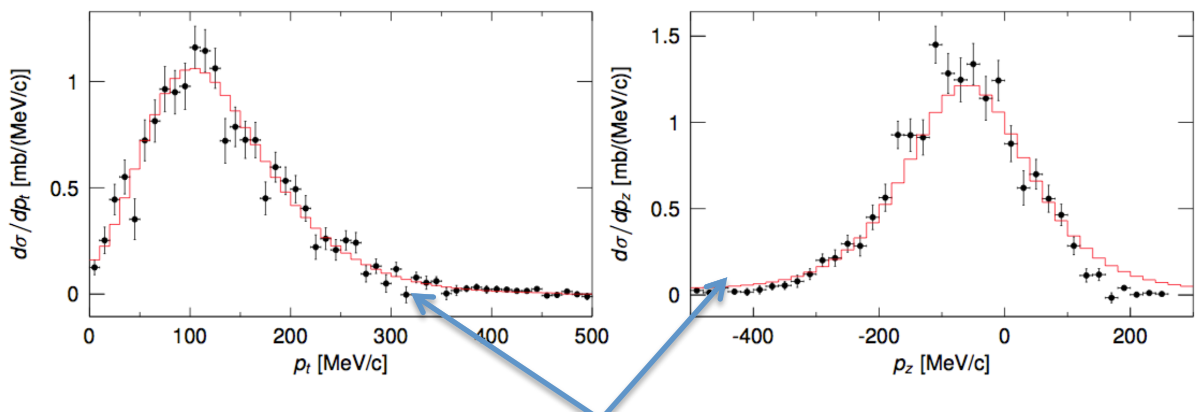

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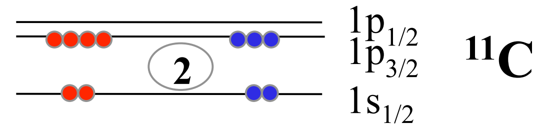

Analysis by M. Holl

Momentum distributions for $^{A}O(p,2p)^{A-1}N$ and $(p,pn)^{A-1}O$

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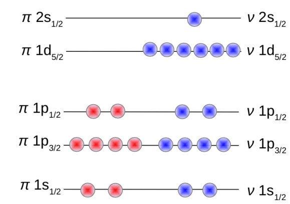
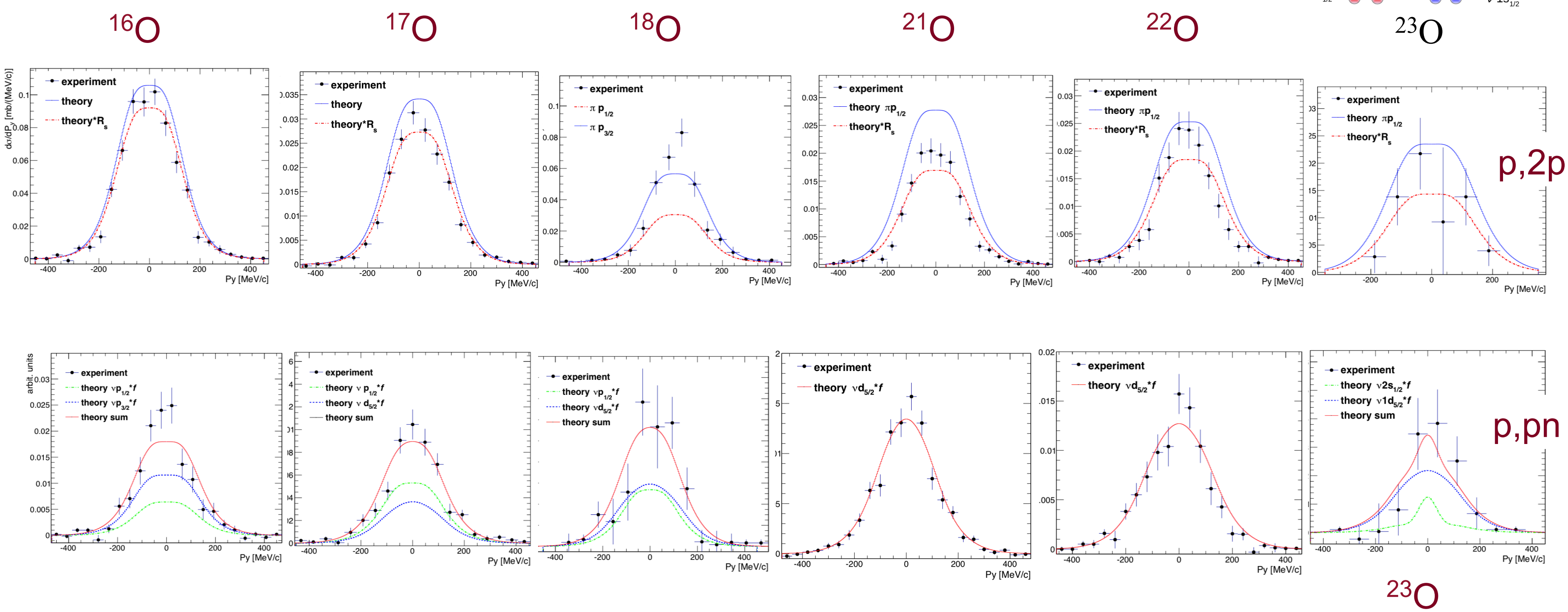
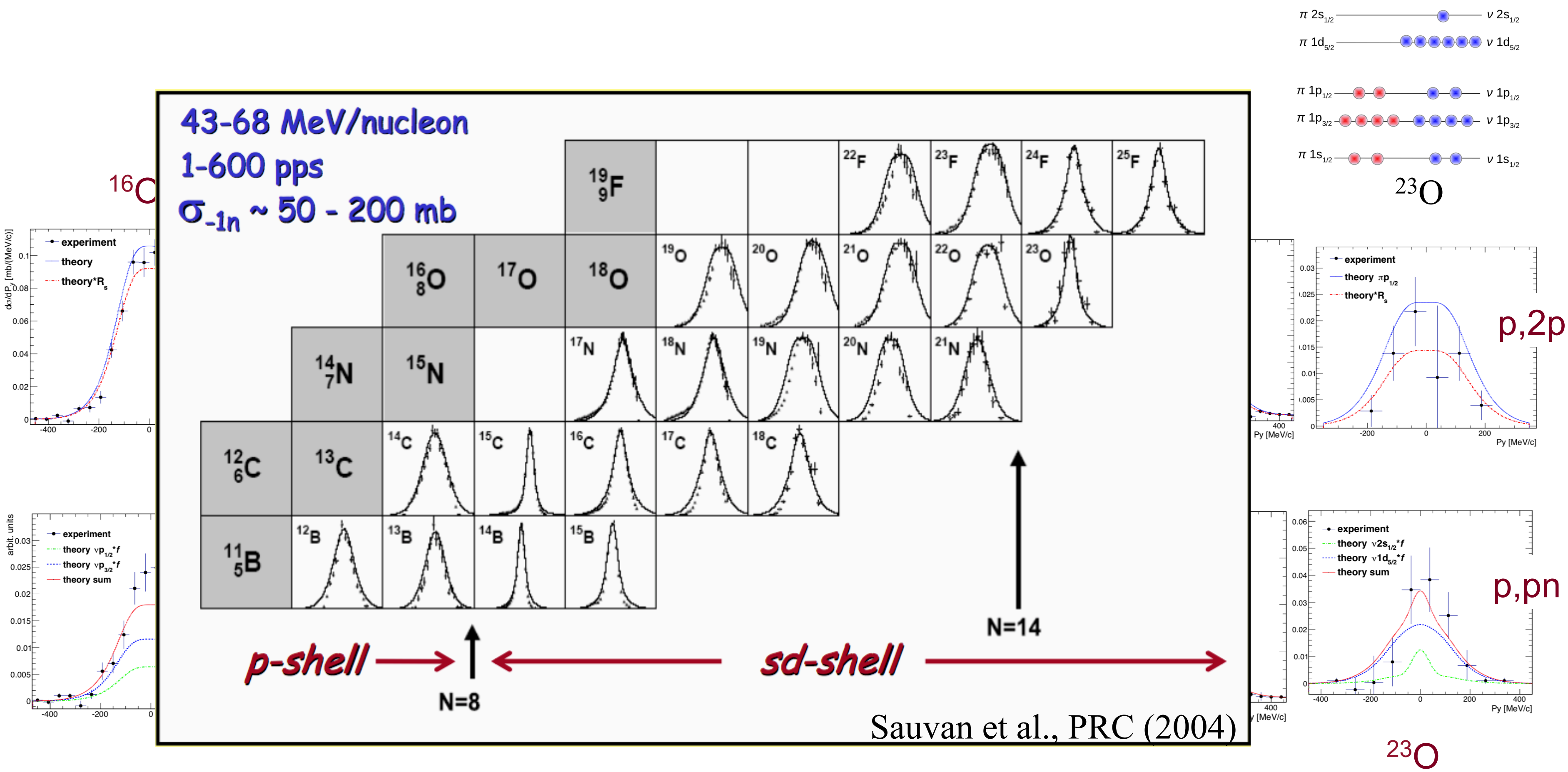




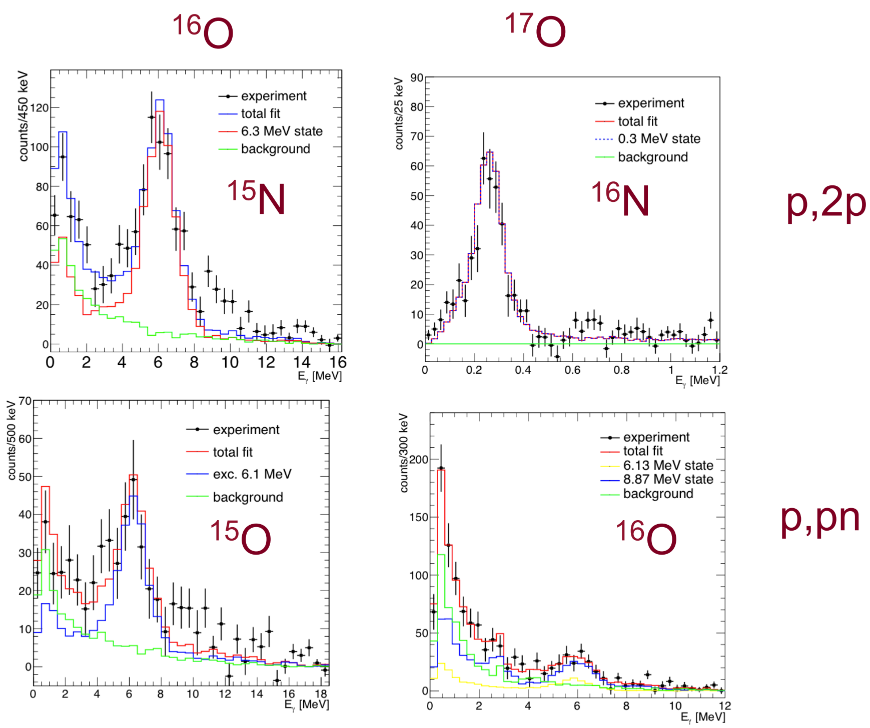
Analysis by L. Atar, reaction theory by C. A. Bertulani

Momentum distributions for $^{A}O(p,2p)^{A-1}N$ and $(p,pn)^{A-1}O$



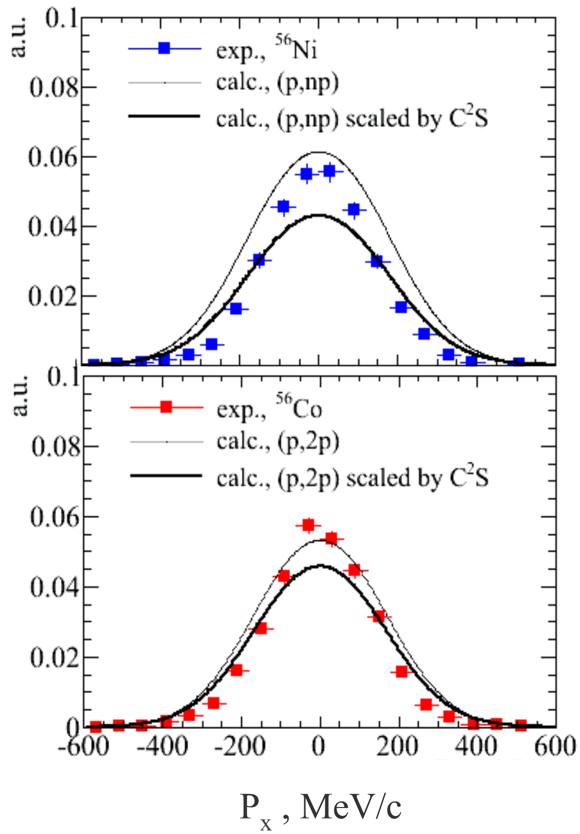
Analysis by L. Atar, reaction theory by C. A. Bertulani

Gamma-ray spectra for $^{A}O(p,2p)^{A-1}N$ and $(p,pn)^{A-1}O$



Analysis by L. Atar

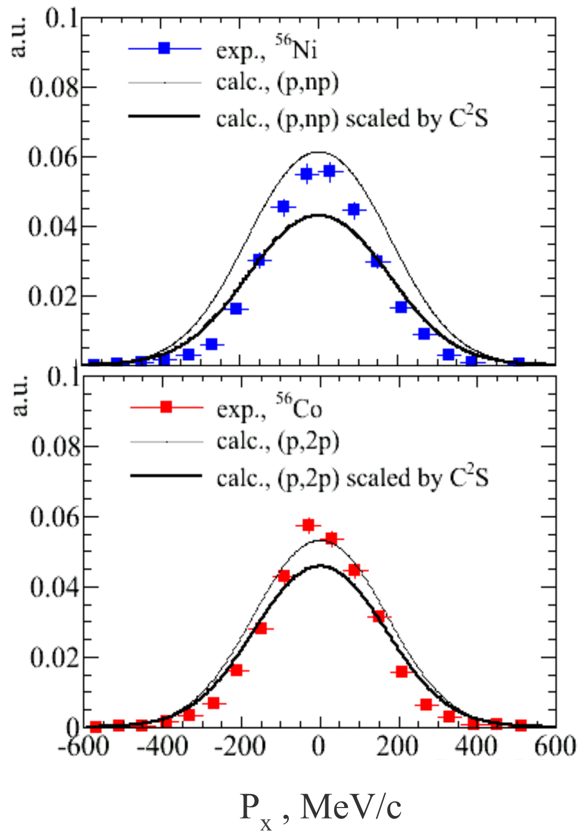
Inclusive (p,2p) and (p,pn) Ni

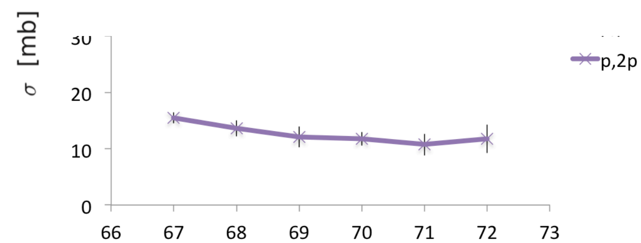


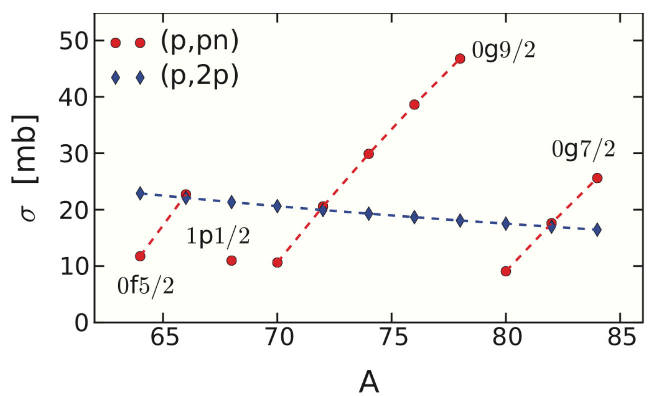
From what we have seen so far: theoretical calculations work better for light nuclei in terms of momentum width

Analysis by A. Movsesyan

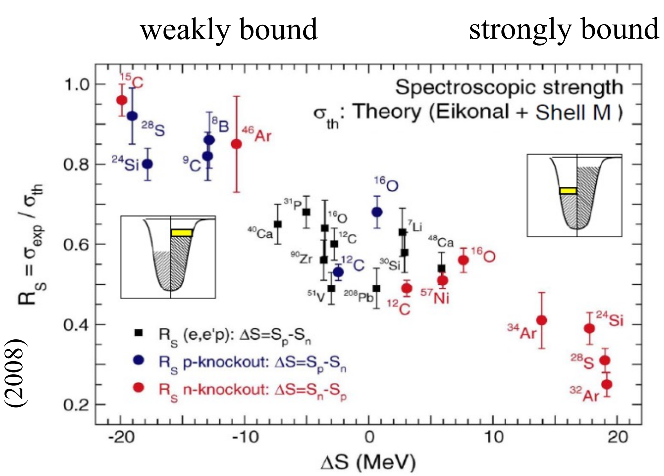
Inclusive (p,2p) and (p,pn) Ni



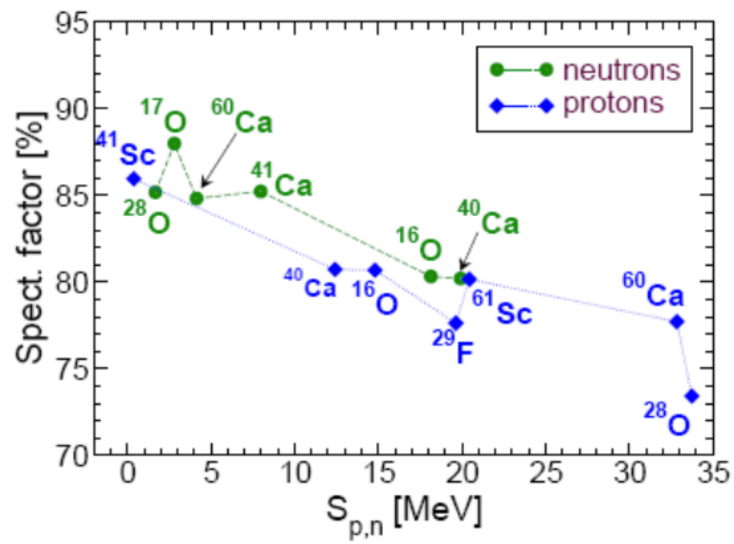




Quenching of spectroscopic factors from inclusive p,2p



A. Gade, *et.al.* PRC 77, 044306 (2008)

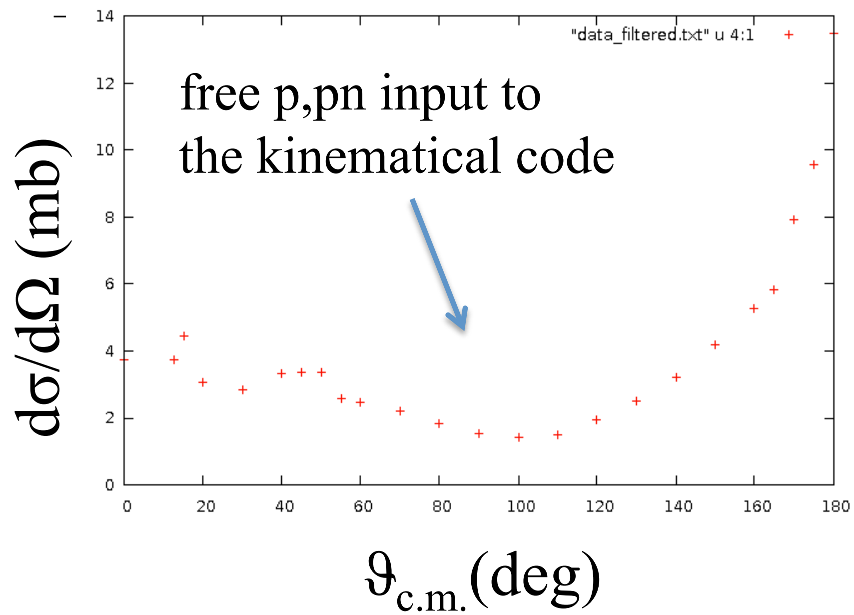


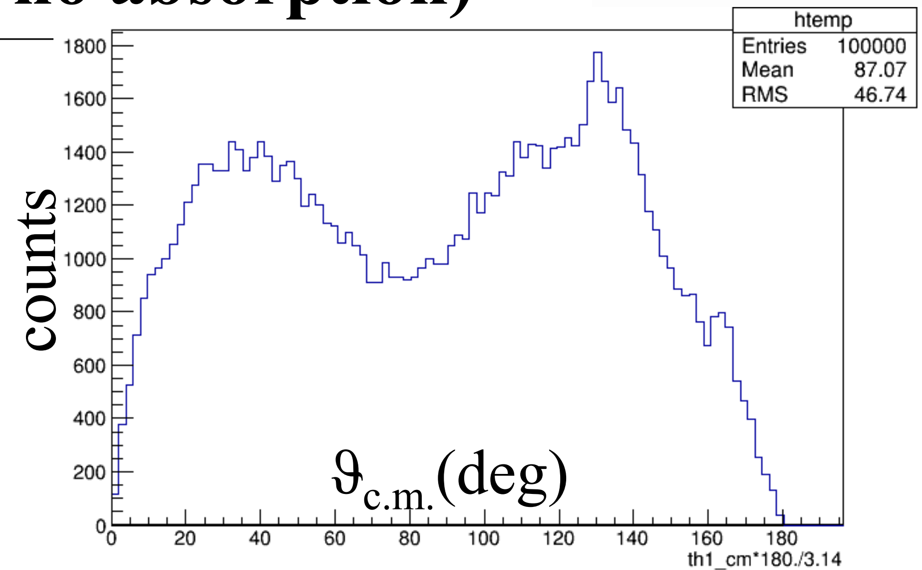
SPECTROSCOPIC FACTORS IN ^{16}O AND NUCLEON ASYMMETRY

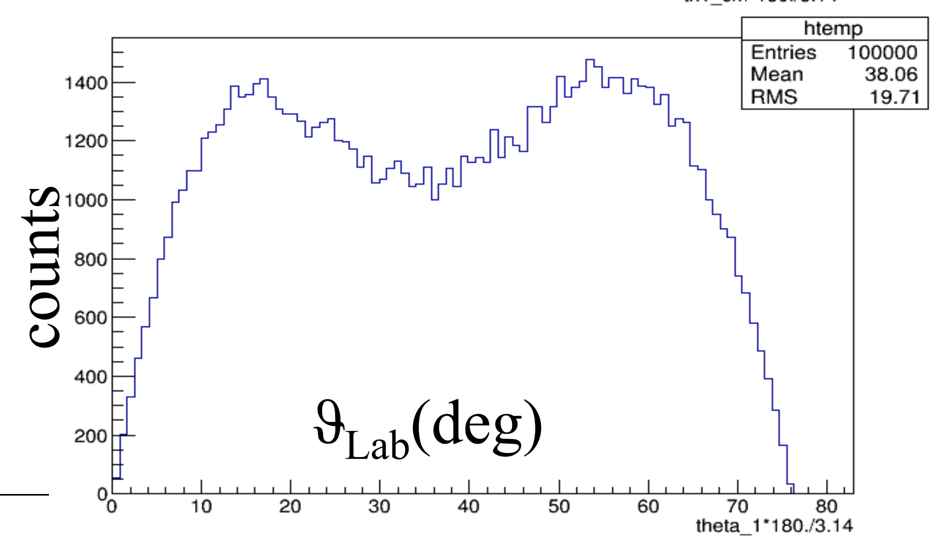
arXiv:0901.1920v1 [nucl-th] 14 Jan 2009

C. Barbieri

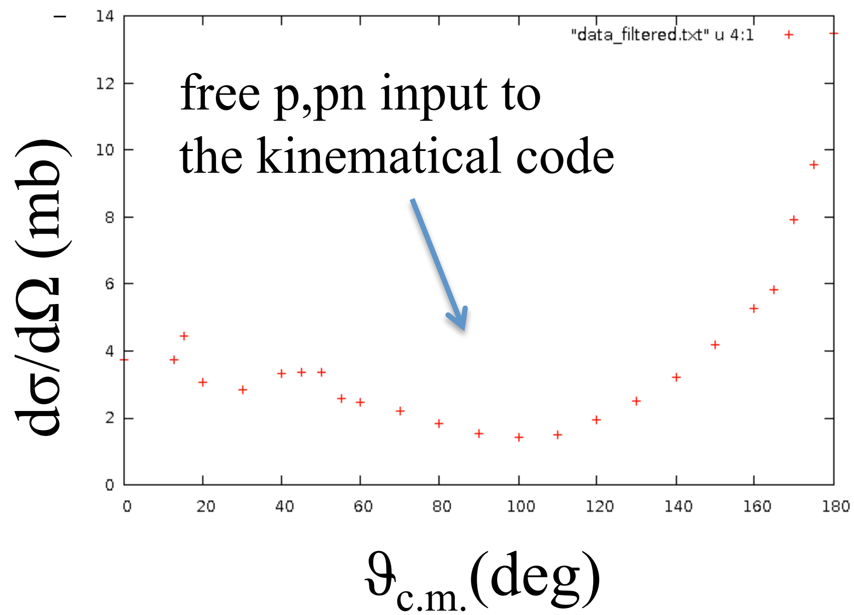
Output of kinematical code for the $^{12}C(p,pn)$ case (i.e. no absorption)

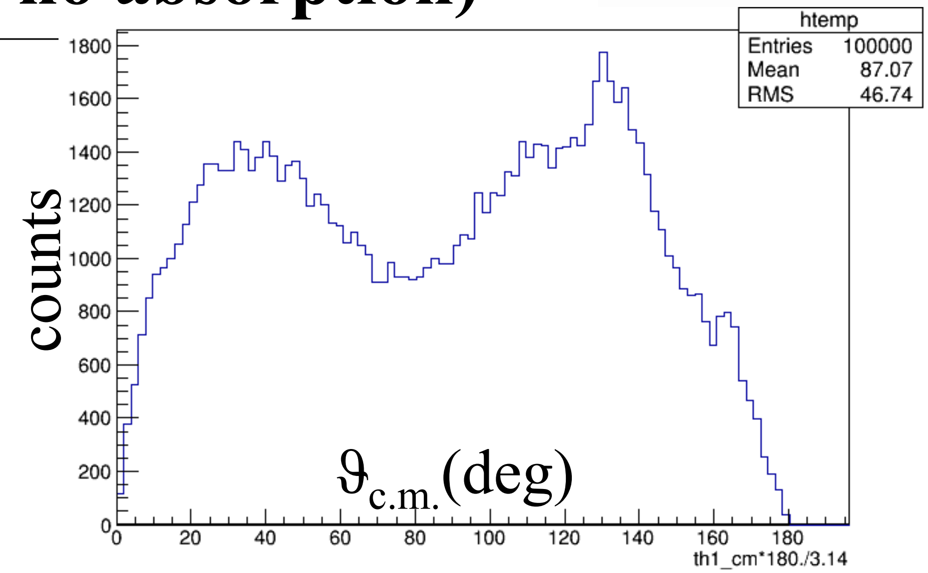


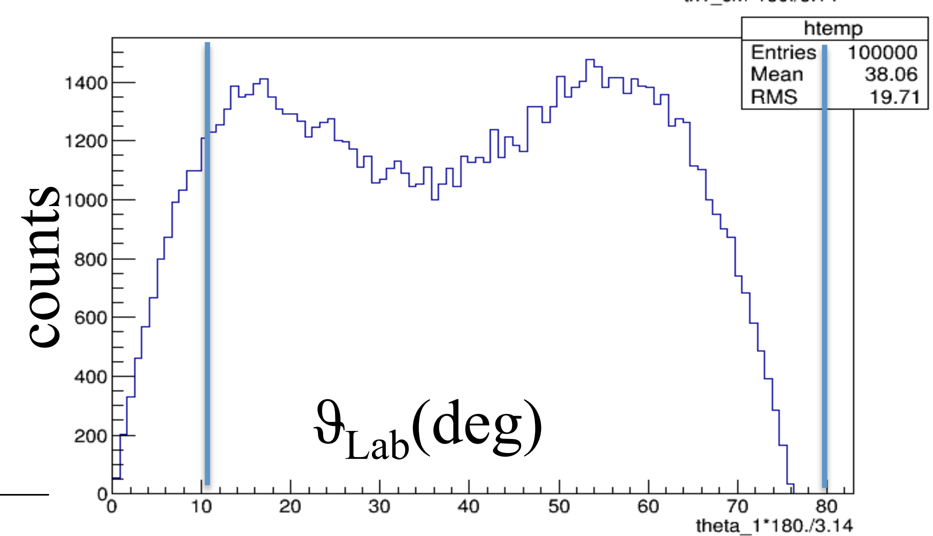




Output of kinematical code for the ^{12}C(p,pn) case (i.e. no absorption)







Output of kinematical code for the $^{12}C(p,pn)$ case (i.e. no absorption)

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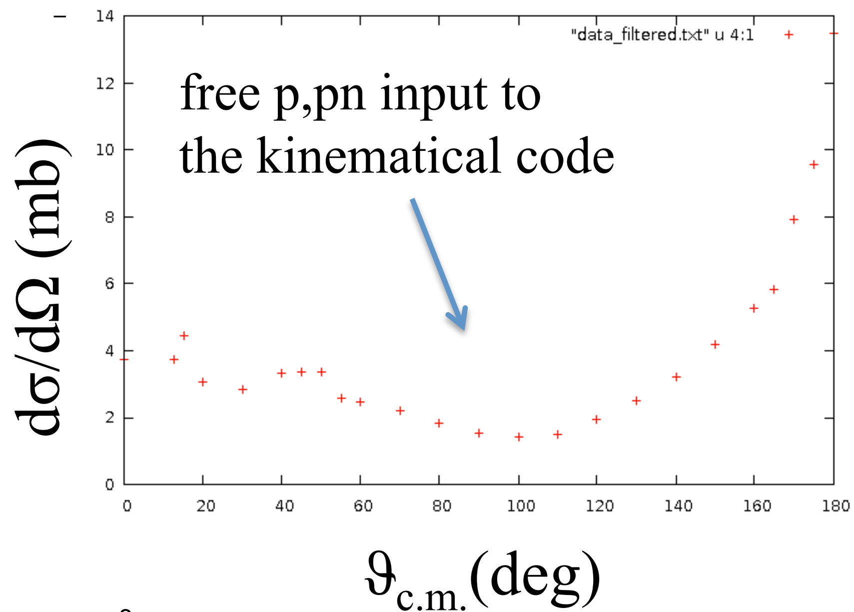

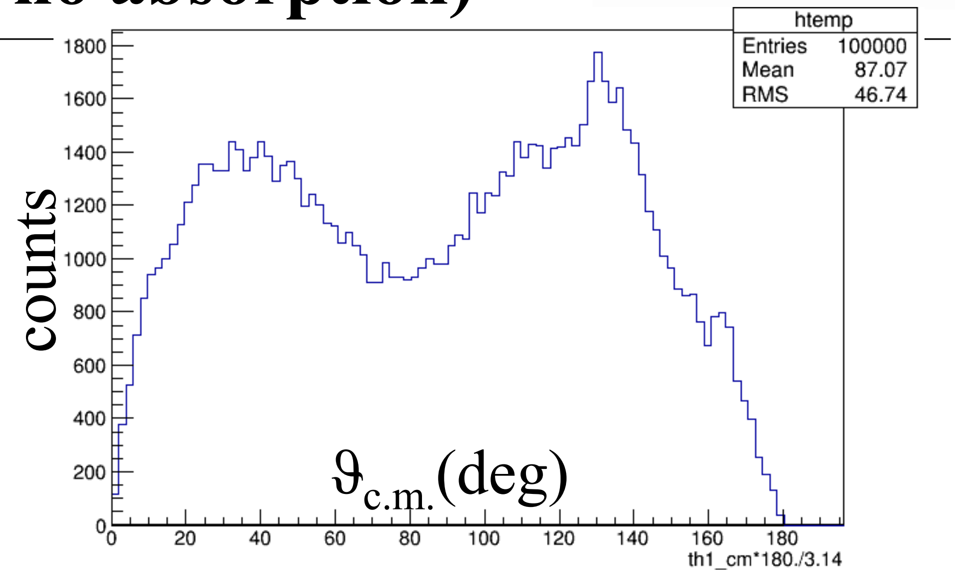

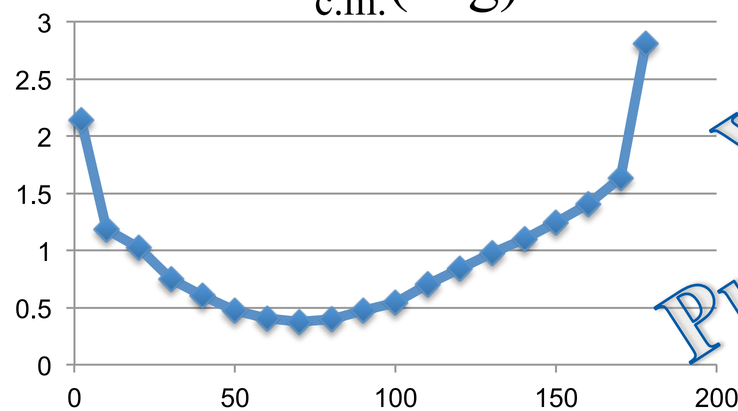

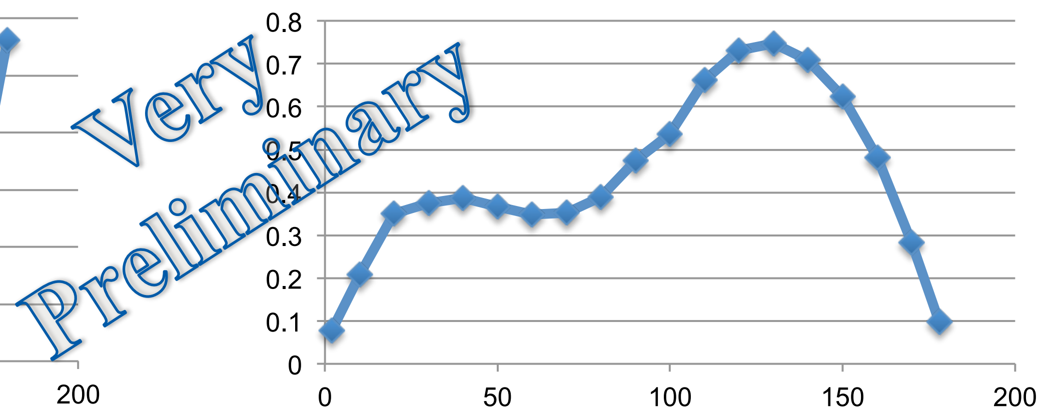

Nuclei beyond the drip line @ R^3B
"First observation of ^{15}Ne ground and excited states"

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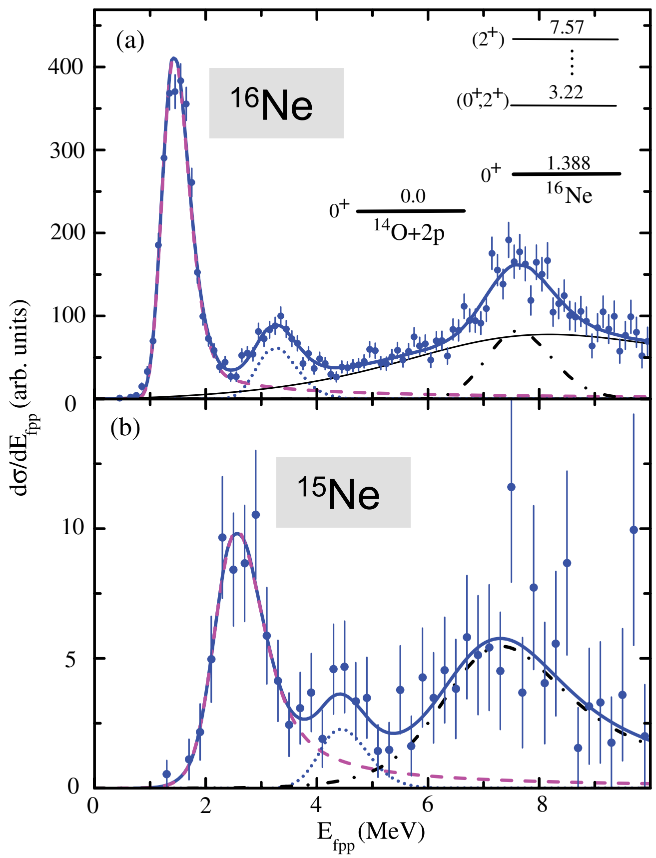
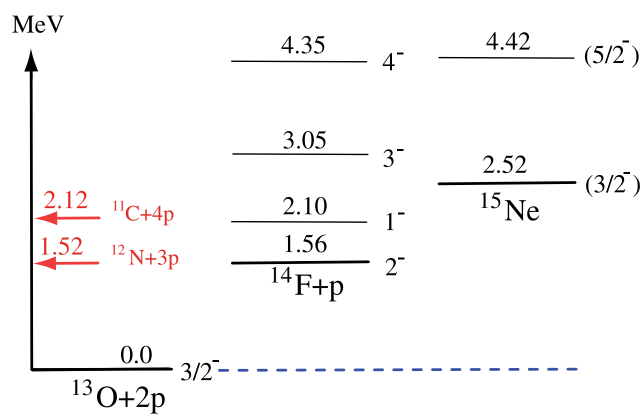
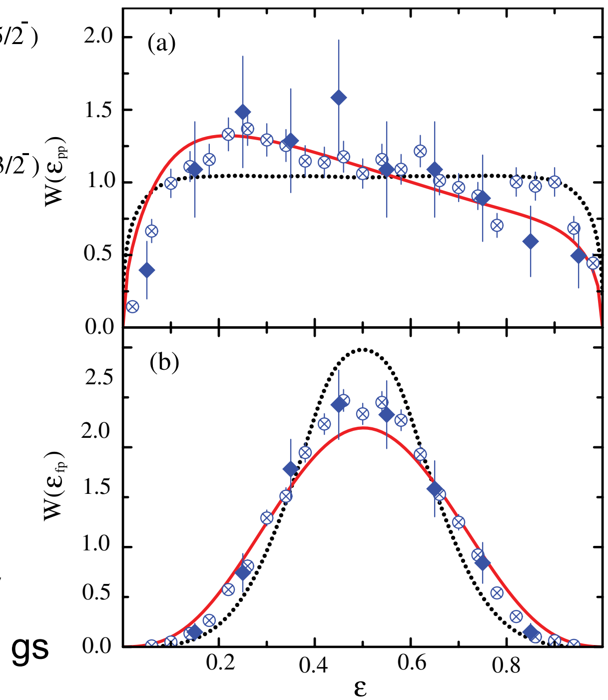


^{15}Ne and daughter nuclei



^{15}Ne 3-body decay

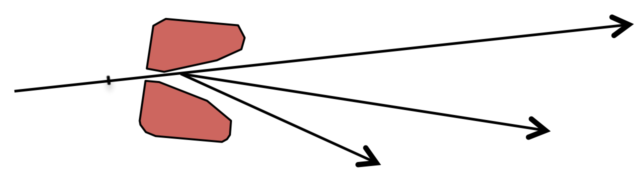


⊗ ^{16}Ne exp data

◆ ^{15}Ne exp data

^{16}Ne isotropic 3-body decay

sequential decay via the ^{14}F gs

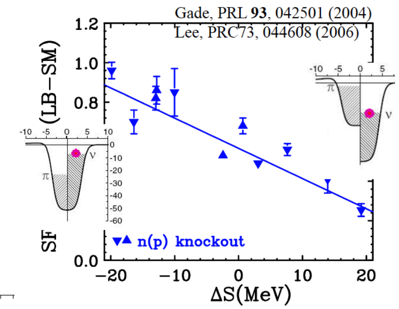


^{15}Ne ground state unbound by S_{2p} = 2.522(66) MeV

F. Wamers et al., Phys. Rev. Lett. 112 (2014) 132502

Short-Range Correlations (SRC)

- 60-70% of nucleons in nuclei are in single-particle mean-field orbitals
- The rest are in long- and short-range correlated pairs
    - Mainly SRC correlated pairs, and most of them are pn pairs



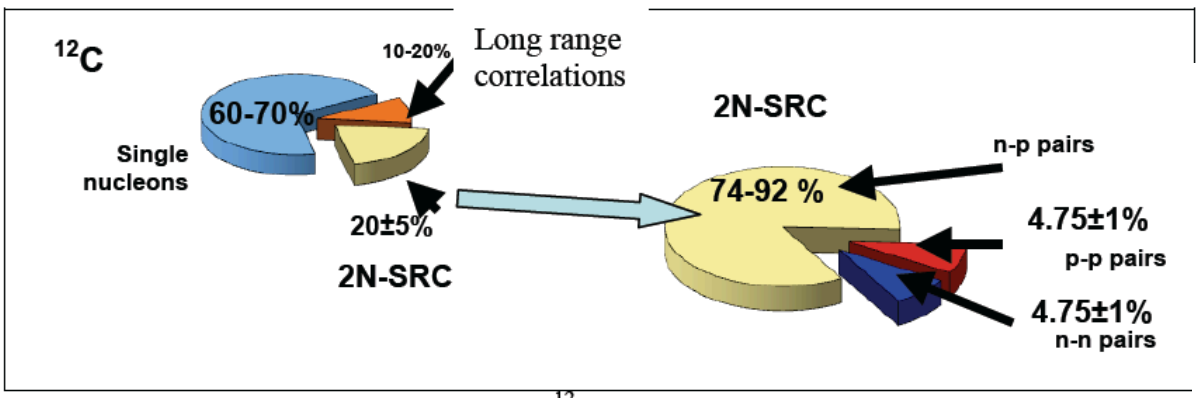
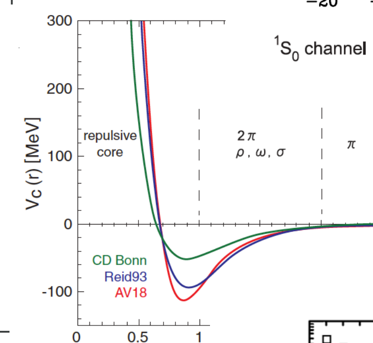
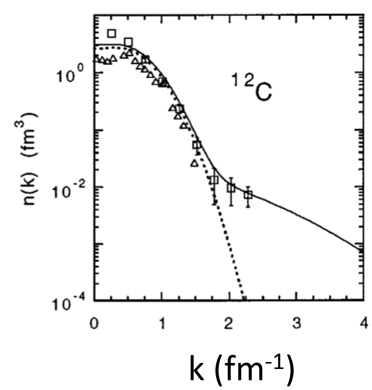


Figure from O. Hen *et al.* “A proposal to Jefferson Lab PAC 38, Aug. 2011”





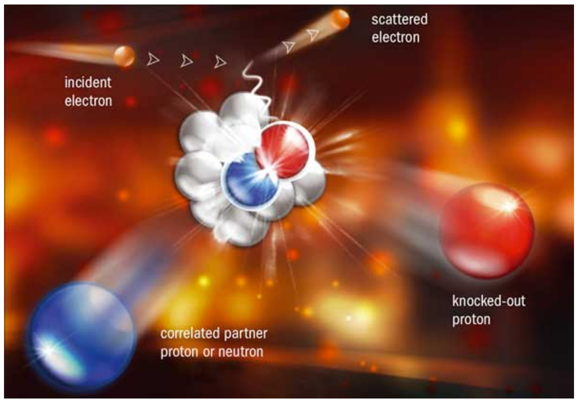
C. Ciofi degli Atti PRC 53 (1996) 1689

SRC arises from the repulsive core of the NN interaction

➢ Responsible for the high momentum component of the nuclear wavefunction

Probes

Most of our knowledge about SRC has been obtained from electron scattering experiments on a fixed target at large momentum transfer, performed e.g. at JLab.

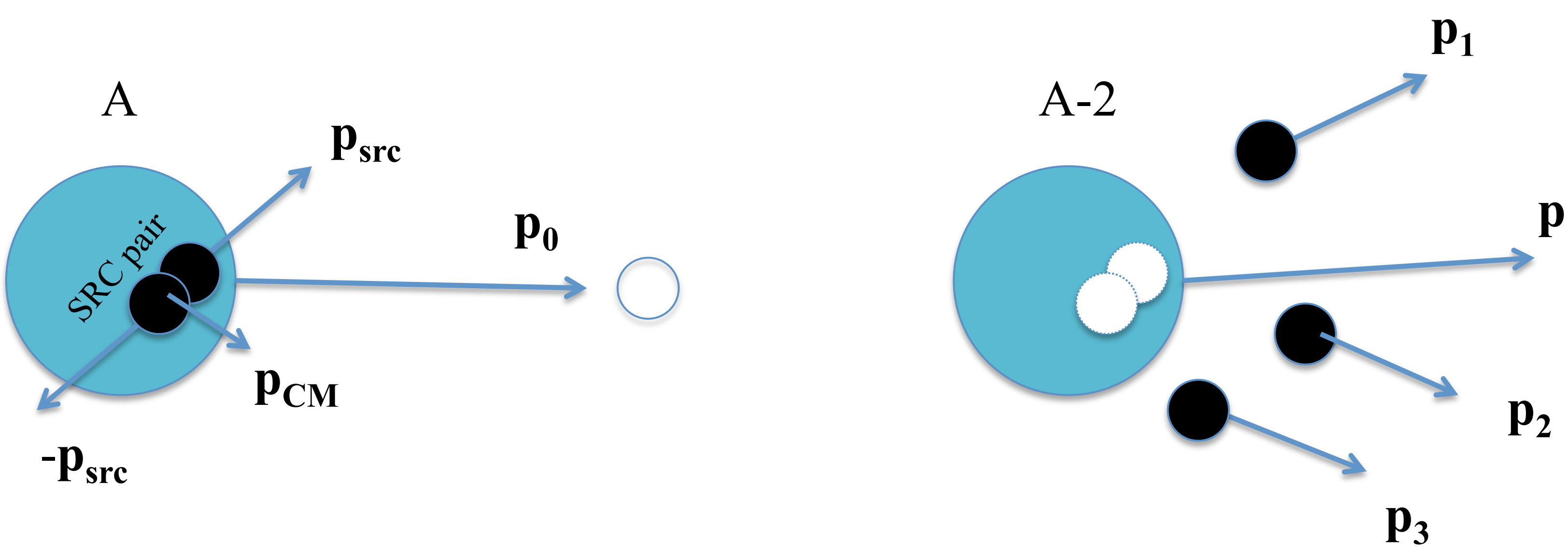


Some References:
K. S. Egiyan *et al.*, Phys. Rev. C 68 (2003) 014313.
K. S. Egiyan *et al*, Phys. Rev. Lett. 96 (2006) 082501.
R. Subedi *et al.*, Science 320 (2008) 1476.
R. Shneor *et al.*, Phys. Rev. Lett. 99 (2007) 072501.
M. M. Sargsian *et al.*, Phys. Rev. C 71 (2005) 044615.
R. Schiavilla *et al.*, Phys. Rev. Lett. 98 (2007) 132501.

Radioactive beams → require electron-ion scattering in a storage ring (e.g. ELISe project at FAIR).

Instead, use hadronic probes (proton target) → study SRC in exotic nuclei.

Probes



- SRC in inverse kinematics with a hydrogen target → access exotic nuclei.
- part of the QFS reactions for large momentum tranfser

Summary

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- Quasi-free scattering
  - QFS is successfully applied in inverse kinematics
  - Rich data sets covering a wide range of nuclei are under analysis
  - Rich future physics program: shell structure, cluster structure, unbound nuclei, N-N correlations ….

- R3B Setup @ GSI/FAIR ideal for such investigations

- reaction theory by C. Bertulani provides a good understanding of the data

Thank you for your attention!

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Aksouh, F.; Al-Khalili, J.; Algora, A.; Alkhasov, G.; Altstadt, S.; Alvarez, H.; Atar, L.; Audouin, L.; Aumann, T.; Pellereau, E.; Martin, J.-F.; Gorbinet, T.; Seddon, D.; Kogimtzis, M.; Avdeichikov, V.; Barton, Ch.; Bayram, M.; Belier, G.; Bemmerer, D.;Bendel, M.; Benlliure, J.; Bertulani, C.; Bhattacharya, S.; Bhattacharya, Ch.; Le Bleis, T.; Boilley, D.; Boretzky, K.; Borge, M. J.; Botvina, A.; Boudard, A.; Boutoux, G.; Boehmer, M.; Caesar, C.; Calvino, F.; Casarejos, E.; Catford, W.; Cederkall, J.; Cederwall, B.; Chapman, R.; Charpy, A.; Chartier, M.; Chatillon, A.; Chen, R.; Christophe, M.; Chulkov, L.; Coleman-Smith, P.; Cortina, D.; Crespo, R.; Csatlos, M.; Cullen, D.; Czech, B.; Danilin, B.; Davinson, T.; Diaz, P.; Dillmann, I; Fernandez Dominguez, B; Ducret, J-E.; Duran, I.; Egelhof, P.; Elekes, Z.; Emling, H.; Enders, J.; Eremin, V.; Ershov, S. N.; Ershova, O.; Eronen, S.; Estrade, A.; Faestermann, T.; Fedorov, D.; Feldmeier, H.; Le Fevre, A.; Fomichev, A.; Forssen, C.; Freeman, S.; Freer, M.; Friese, J.; Fynbo, H.; Gacsi, Z.; Garrido, E.; Gasparic, I.; Gastineau, B.; Geissel, H.; Gelletly, W.; Genolini, B.; Gerl, J.; Gernhaeuser, R.; Golovkov, M.l; Golubev, P.l; Grant, A.; Grigorenko, L.; Grosse, E.; Gulyas, J.; Goebel, K.; Gorska, M.; Haas, O. S; Haiduc, M.; Hasegan, D.; Heftrich, T.; Heil, M.; Heine, M.; Heinz, A.; Henriques,A.; Hoffmann, J; Holl, M.; Hunyadi, M.; Ignatov, A.; Ignatyuk, A. V.; Ilie, C. M.; Isaak, J.; Isaksson, L.; Jakobsson, B.; Jensen, A.; Johansen, J.; Johansson, H.; Johnson, R.; Jonson, B.; Junghans, A.; Jurado, B.; Jaehrling, S.; Kailas, S.; Kalantar, N.; Kalliopuska, J.; Kanungo, R.; Kelic-Heil, A.; Kezzar, K.; Khanzadeev, A.; Kissel, R.; Kisselev, O.; Klimkiewicz, A.; Kmiecik, M.; Koerper, D.; Kojouharov, I.; Korsheninnikov, A.; Korten, W.; Krasznahorkay, A.; Kratz, J. V.; Kresan, D.; Krivchitch,A.; Kroell, T.; Krupko, S.; Kruecken, R.; Kulessa, R.; Kurz, N.; Kuzmin, E.; Labiche, M.; Langanke, K.l-H.; Langer, C.; Lapoux, V.; Larsson, K.; Laurent, B.; Lazarus, I.; Le, X. Ch.; Leifels, Y.; Lemmon, R.; Lenske, H.; Lepine-Szily, A.; Leray, S.; Letts, S.; Li, S.; Liang, X.; Lindberg, S.; Lindsay, S.; Litvinov, Y.; Lukasik, J.; Loeher, B.; Mahata, K.; Maj, A.; Marganiec, J.; Meister, M.; Mittig, W.; Movsesyan, A.; Mutterer, M.; Muentz, C.; Nacher, E.; Najafi, A.; Nakamura, T.; Neff, T.; Nilsson, T.; Nociforo, C.; Nolan, P.; Nolen, J.; Nyman, G.; Obertelli, A.; Obradors, D.; Ogloblin, A.; Oi, M.; Palit, R.; Panin, V.; Paradela, C.; Paschalis, S.; Pawlowski, P.; Petri, M.; Pietralla, N.; Pietras, B.; Pietri, S.; Plag, R.; Podolyak, Z.; Pollacco, E.; Potlog, M.; Datta Pramanik, U.; Prasad, R.; Fraile Prieto, L. M.; Pucknell, V.; Galaviz -Redondo, D.; Regan, P.; Reifarth, R.; Reinhardt, T.; Reiter, P.; Rejmund, F.; Ricciardi, M. V.; Richter, A.; Rigollet, C.; Riisager, K.; Rodin, A.; Rossi, D.; Roussel-Chomaz, P.; Gonzalez Rozas, Y.; Rubio, B.; Roeder, M.; Saito, T.; Salsac, M.-D.; Rodriguez Sanchez, J. L.; Santosh, Ch.; Savajols, H.; Savran, D.; Scheit, H.; Schindler, F.; Schmidt, K.-H.; Schmitt, C.; Schnorrenberger, L; Schrieder, G.; Schrock, Ph.; Sharma, M. K.; Sherrill, B.; Shrivastava, A.; Shulgina, N.; Sidorchuk, S.; Silva, J.; Simenel, C.; Simon, H.; Simpson, J.; Singh, P. P.; Sonnabend, K.; Spohr, K.; Stanoiu, M.; Stevenson, P.; Strchan, J.; Streicher, B.; Stroth, J.; Syndikus, I.; Suemmerer, K.; Taieb, J.; Tain, J. L.; Tanihata, I.; Tashenov, S.; Tassan-Got, L.; Tengblad, O.; Teubig, P.; Thies, R.; Togano, Y.; Tostevin, J. A.; Trautmann, W.; Tuboltsev, Y.; Turrion, M.; Typel, S.; Udias-Moinelo, J.; Vaagen, J.; Velho, P.; Verbitskaya, E.; Veselsky, M.; Wagner, A.; Walus, W.; Wamers, F.; Weick, H.; Wimmer, C.; Winfield, J.; Winkler, M.; Woods, Ph.; Xu, H.; Yakorev, D.; Zegers, R.; Zhang, Y.-H.; Zhukov, M.; Zieblinski, M.; Zilges, A.;