The quasi-free scattering program at R^3B

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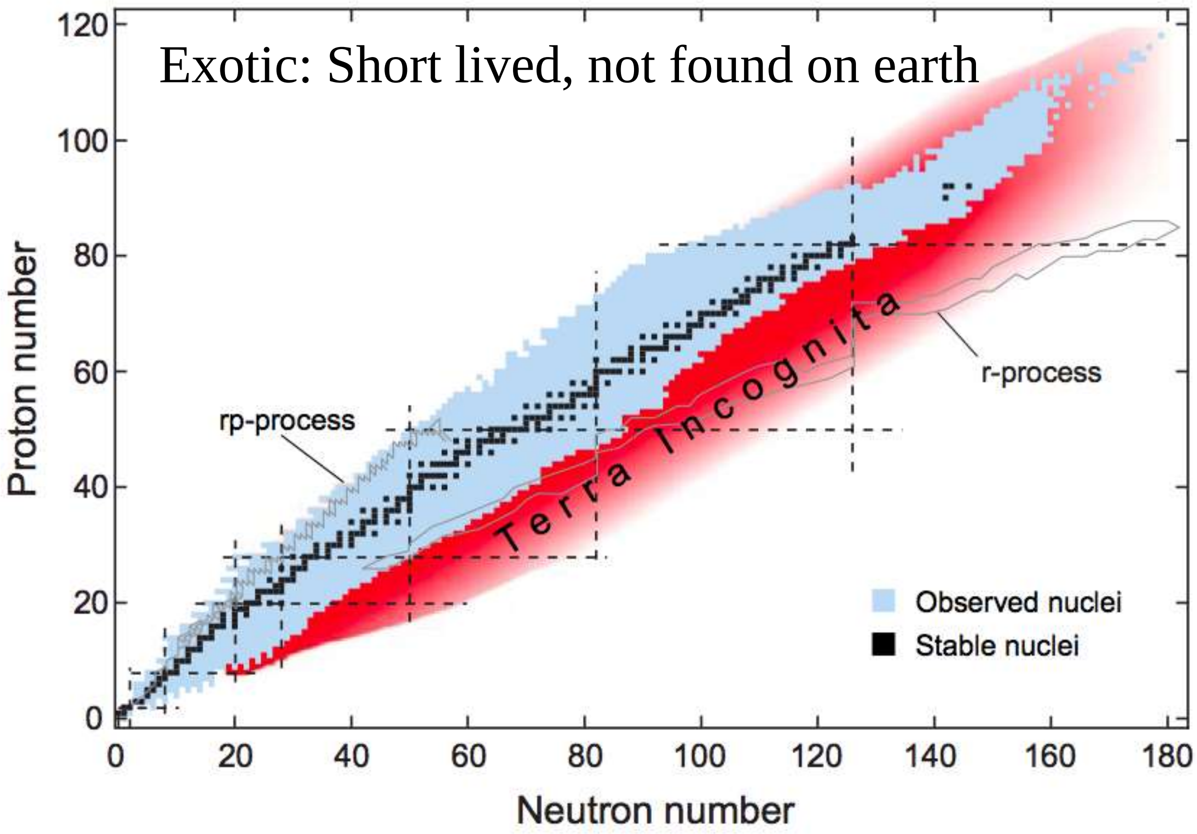
Technical University of Darmstadt

R^3B collaboration

October 13-17 2014, Worms, "ICST for FAIR in Europe 2014"

Stable and exotic nuclei



- There are ~ 300 stable nuclei (black).
- There are ~ 3500 known unstable nuclei.

Picture from
ISF at MSU document

Why do we study exotic nuclei?

- Exotic nuclei are continually created and play a fleeting though important role in the cosmos

- Nuclei are unique mesoscopic systems such as atomic clusters or quantum dots that are important in other fields of physics today

- Fertile ground to study new quantum phenomena, weak binding

- Major advances in many-body theory should result from investigations of nuclei with very different proton-to-neutron admixtures

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

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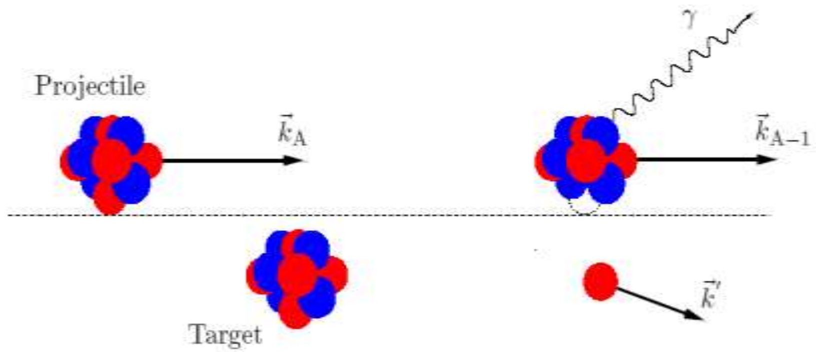
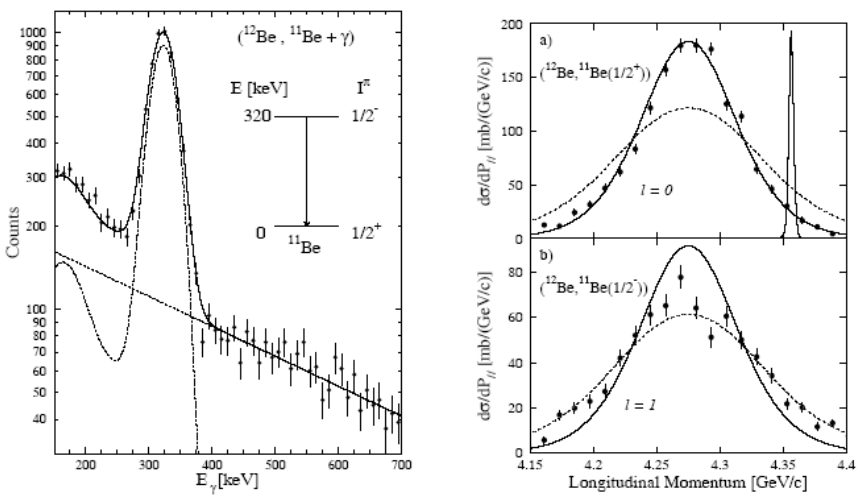


Navin, A. et al. PRL **85** (2000) 266

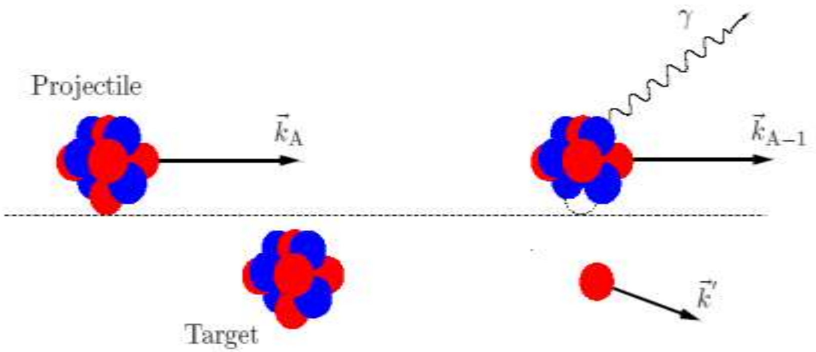


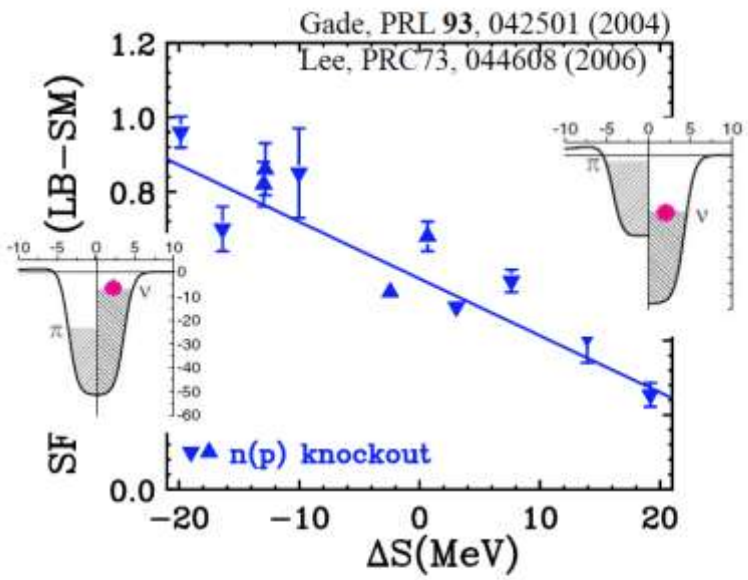
Knockout reactions on light nuclear targets have helped to reveal new quantum phenomena such as the nuclear halo and to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion…

Spectrometer → momentum distributions and Mass ID
γ-ray detector → select final state

Momentum distributions → orb. ang. mom.
Cross sections → spectr. factors

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

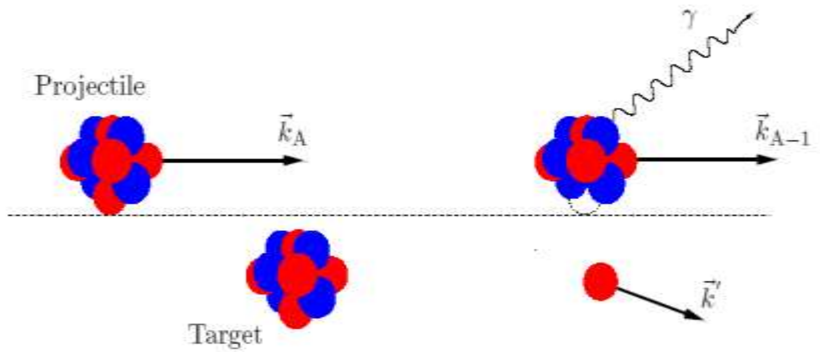




Knockout reactions on light nuclear targets have helped to reveal new quantum phenomena such as the nuclear halo and to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion…

Quenching of spectroscopic factors

Complementary spectroscopic tools

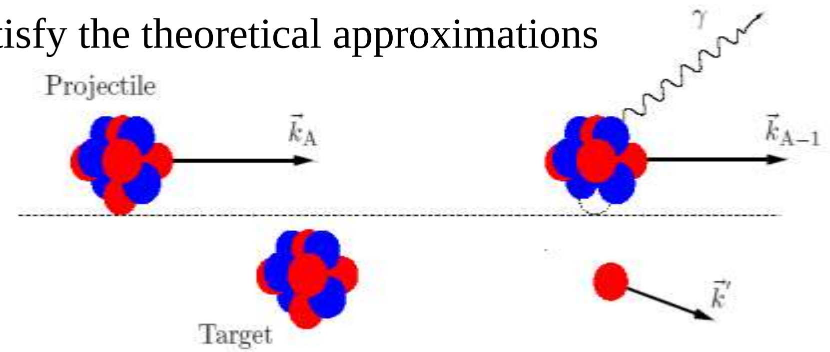


Knockout reactions on light nuclear targets

Strong absorption → surface localized

Complementary spectroscopic tools

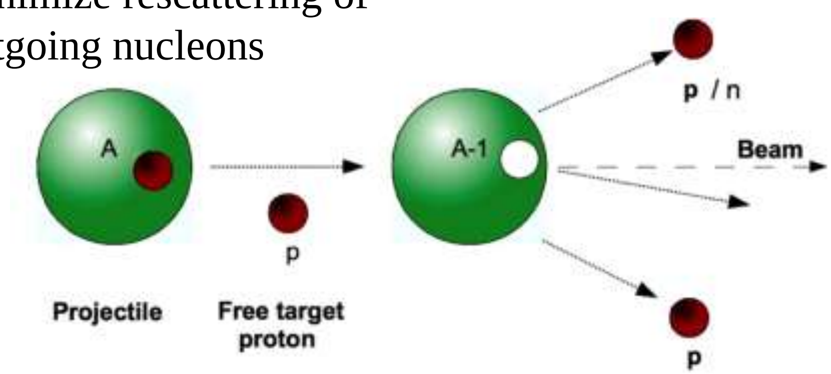
at least few tenths of MeV/A in order to satisfy the theoretical approximations



Knockout reactions on light nuclear targets

Strong absorption → surface localized

few hundred MeV/A to minimize rescattering of outgoing nucleons



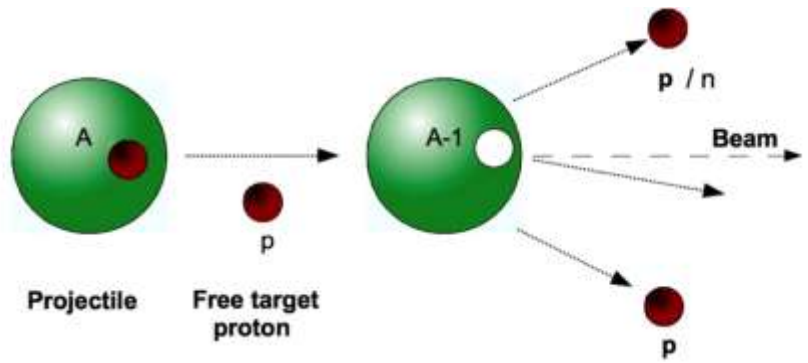
QFS reactions (p, 2p), (p, pn), (p, pα) etc.

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

Complementary spectroscopic tools



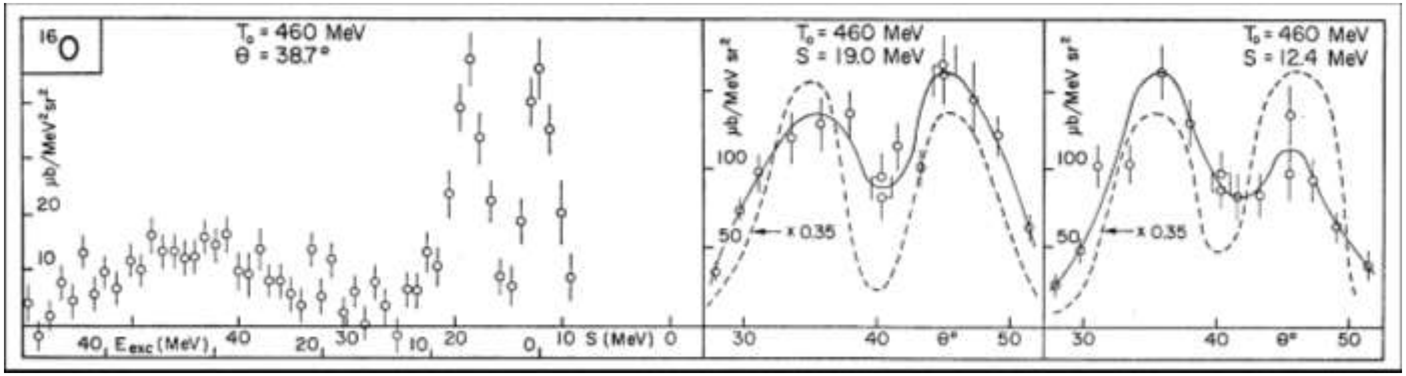
QFS reactions

Spectrometer → momentum distributions and Mass ID

γ-ray detector → select final state

Target recoil detector → detect scattered nucleons

Scattered nucleons → kinematically complete and redundant measurement



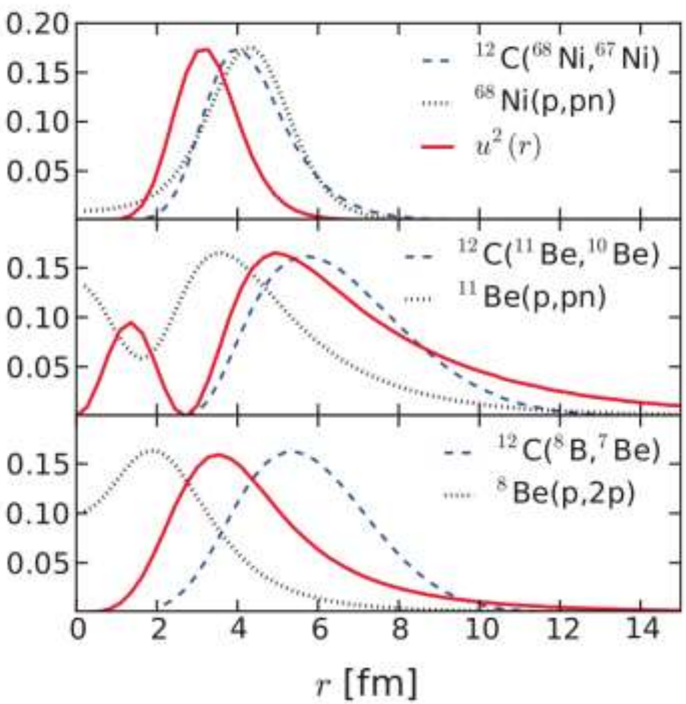
^{16}O (p,2p) in normal kinematics
G. Jacob et al., PLB 45 (1973) 181

QFS calculations by C. A. Bertulani

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

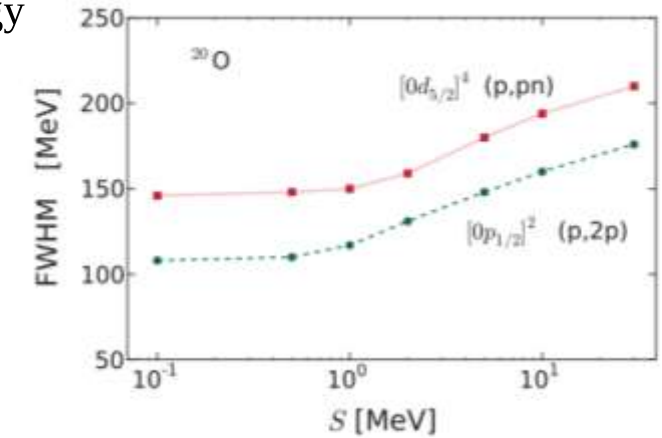
PRC 88, 064610 (2013)

Removal probability:
proton target compared to C target

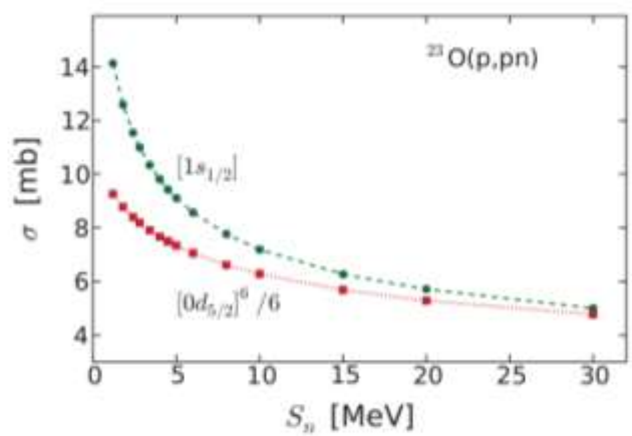


$0f_{7/2}$ orbital in ^{68}Ni

Momentum width dependence on separation energy



Cross section dependence on separation energy



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

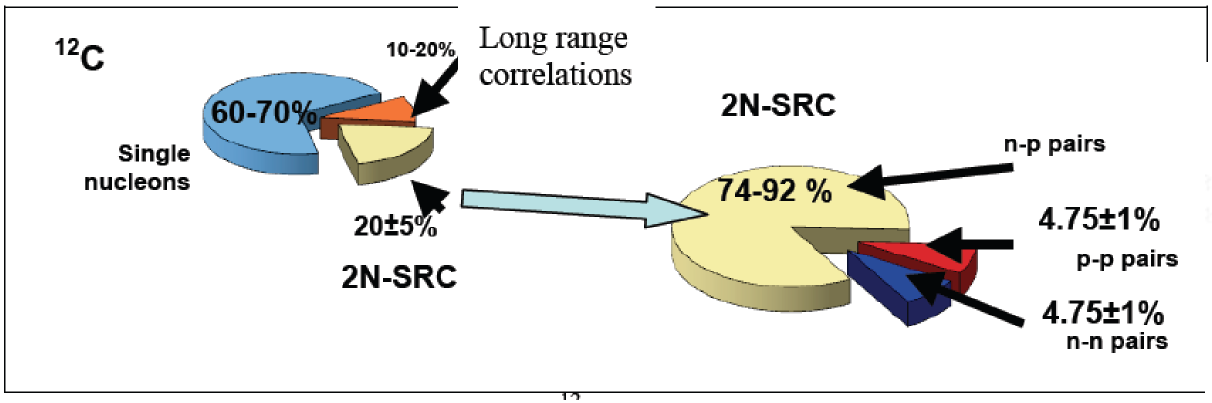
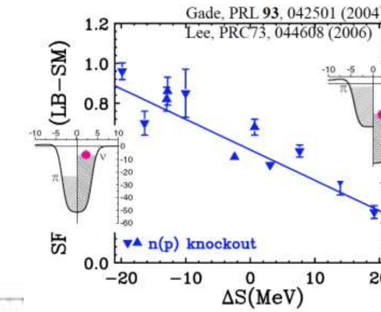
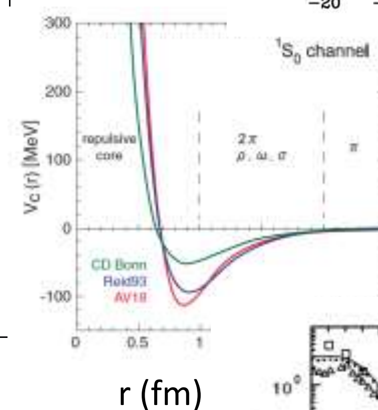
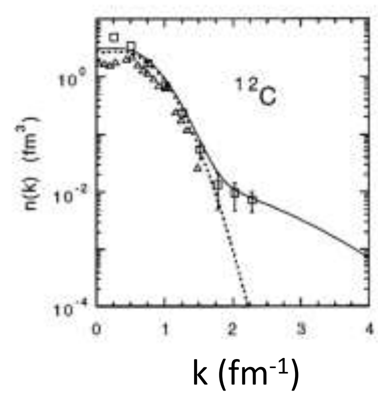


Figure from O. Hen *et al.* “A proposal to Jefferson Lab PAC 38, Aug. 2011”







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

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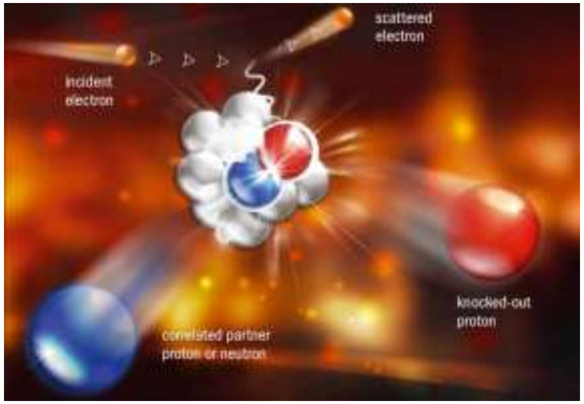
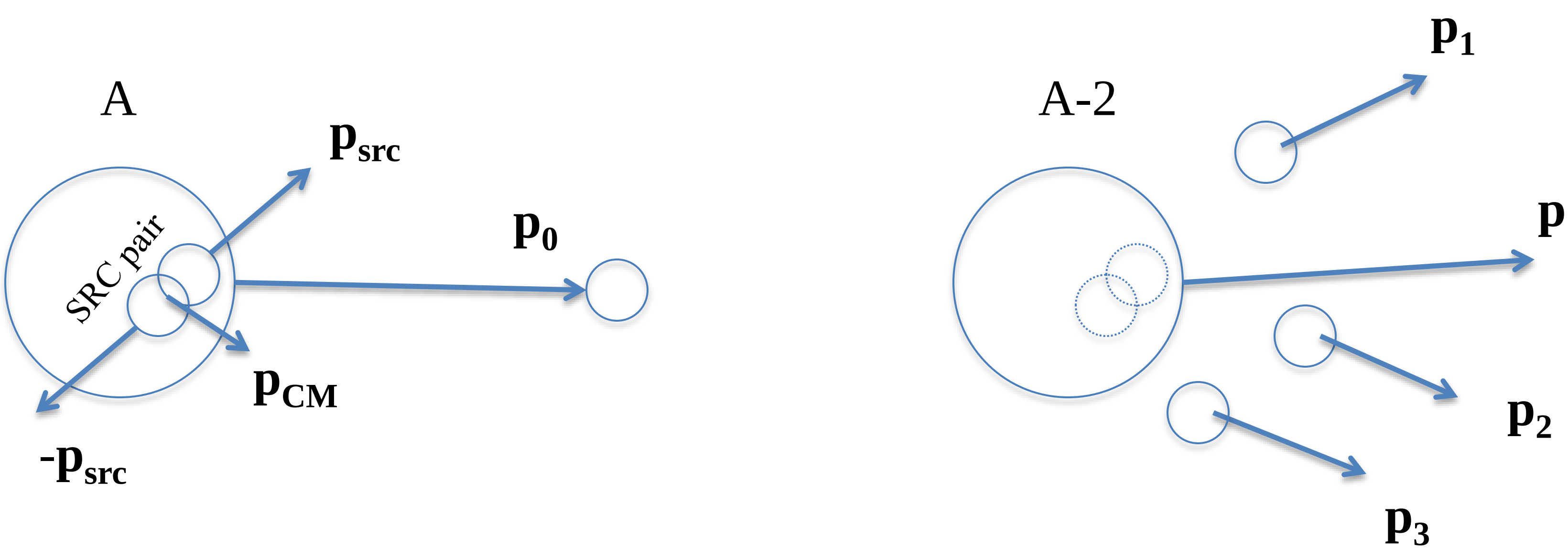
Most of our knowledge about SRC has been obtained from electron scattering experiments on a fixed target at large momentum transfer, performed e.g. at JLab.



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 (2
R. Shneor *et al.*, Phys. Rev. Lett. 99 (2007) 072501. M. M. Sargsian *et al.*, Phys. Rev
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



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

In principle, part of the QFS reactions for large momentum tranfser

Quasi-free scattering constitutes one of the main physics goals of the R^3B collaboration

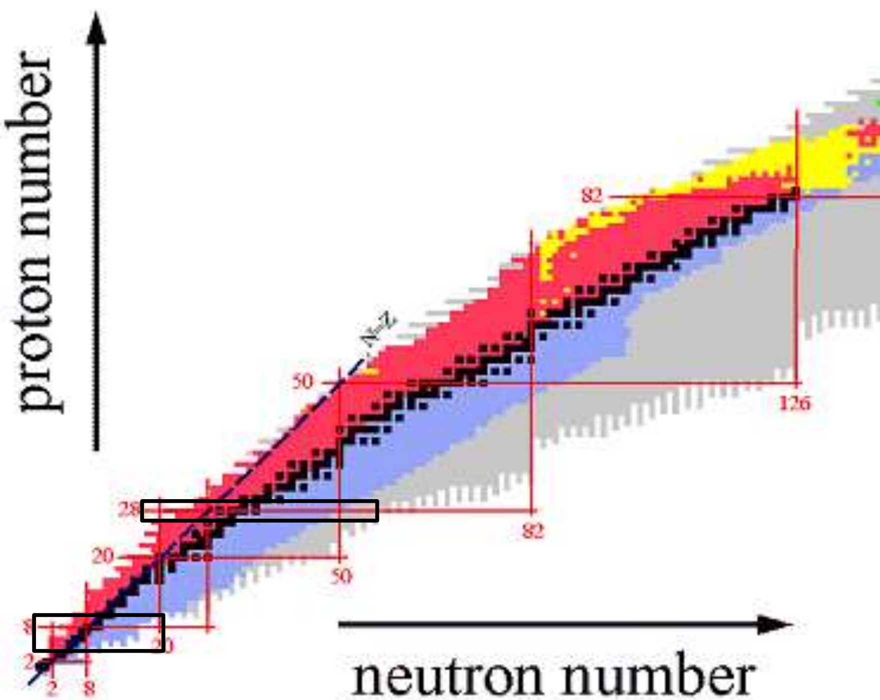
Rich physics cases in available (p,2p and p,pn) QFS data sets obtained with R^{3}B @ GSI

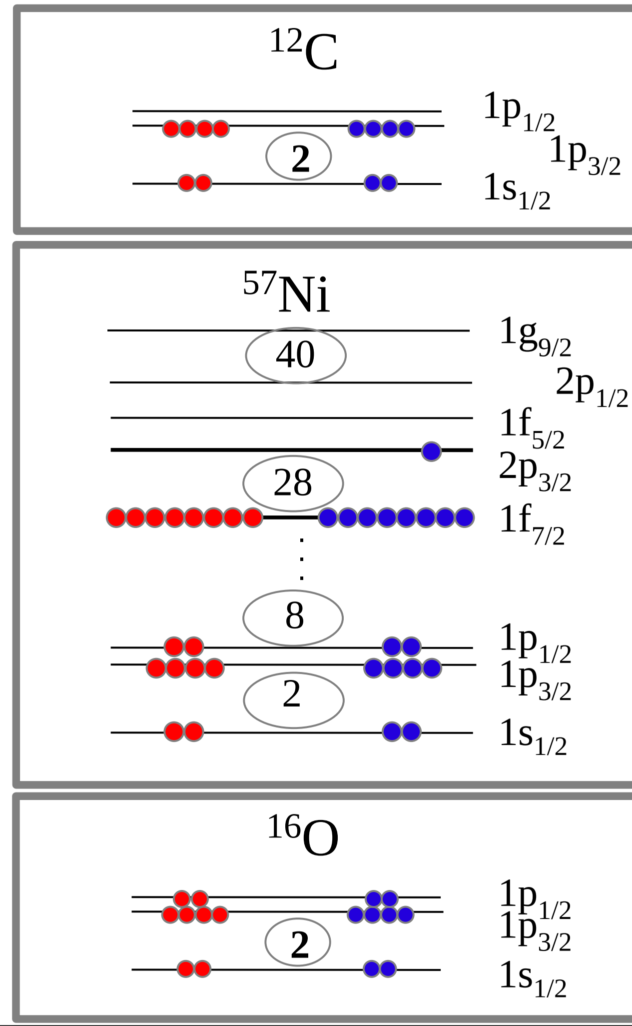
^{12}C isotope: benchmark case
C isotopic chain: Z = 6; N = 4 – 14

Ni isotopic chain : Z = 28; N = 28 – 30, 39 – 44

O isotopic chain : Z = 8; N = 8 – 15

….





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

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^{12}C isotope: benchmark case

C isotopic chain:

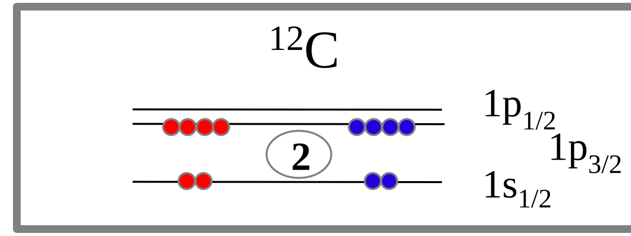
- known up to the drip lines
- accessible to ab-initio theories

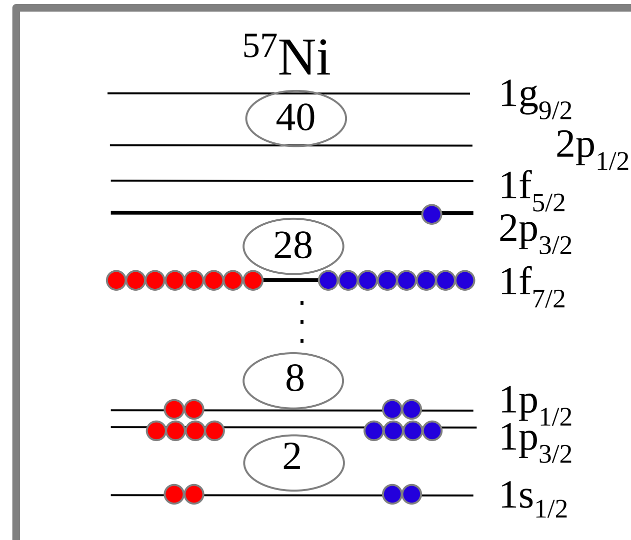
Ni isotopic chain :

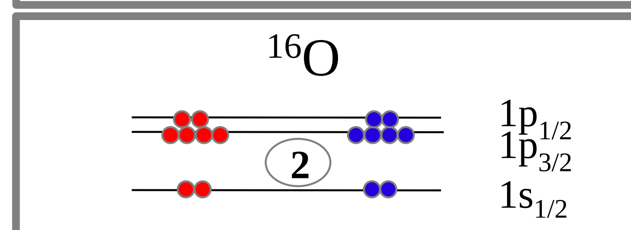
- How magic is ^{68}Ni? – N=40 sub-shell closure
- Shell evolution towards ^{78}Ni
- Close to the "New" island of inversion (^{64}Cr, ^{66}Fe)

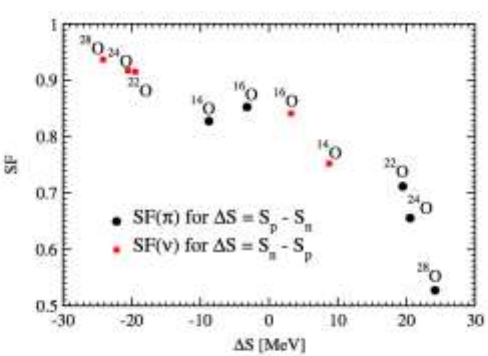
O isotopic chain :

- "unexpected" end of drip line
- large range of separation energies









Jensen et al.,PRL, 107, 032501 (2011)

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

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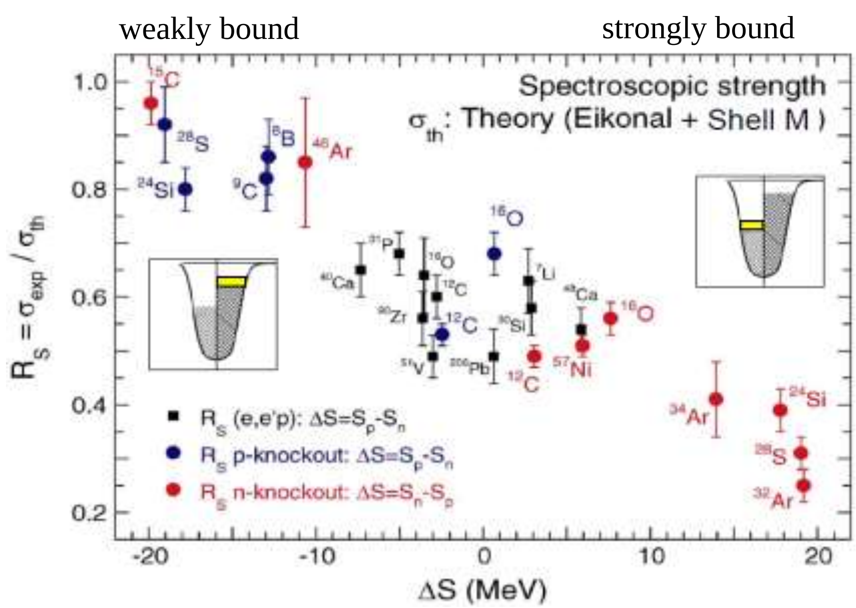
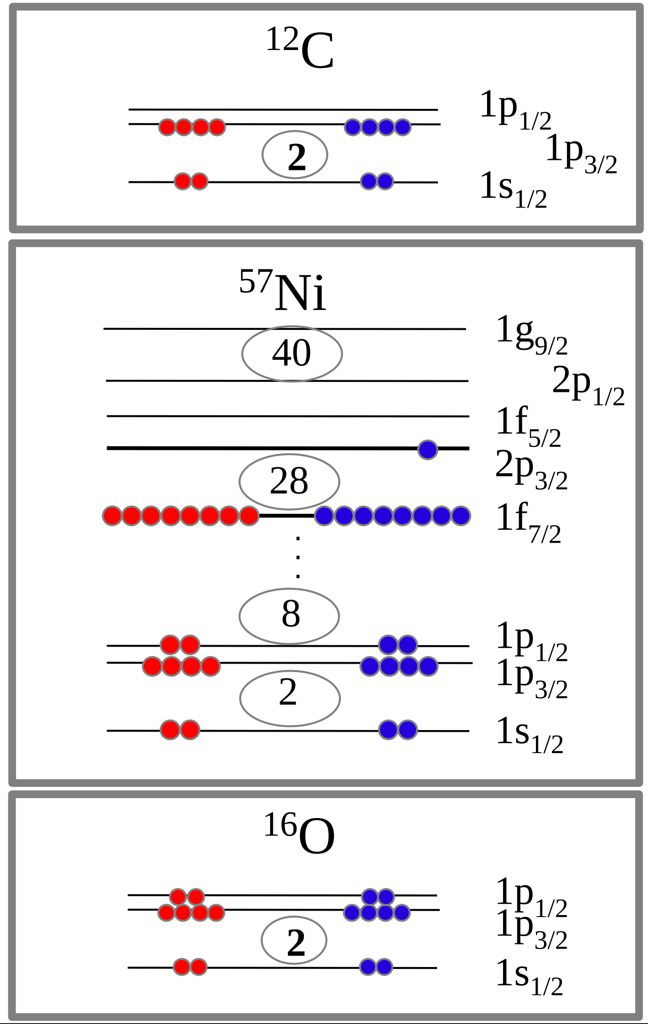
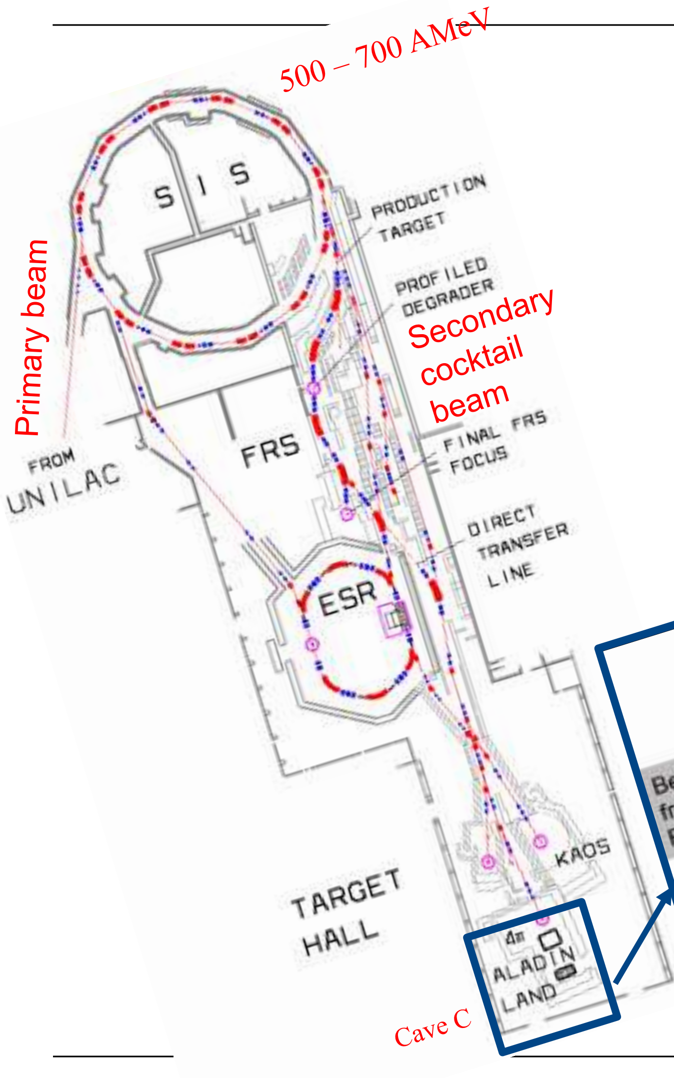
- large range of separation energies and more sensitive to deeply bound states → independent and consistent measurement of reduction factors



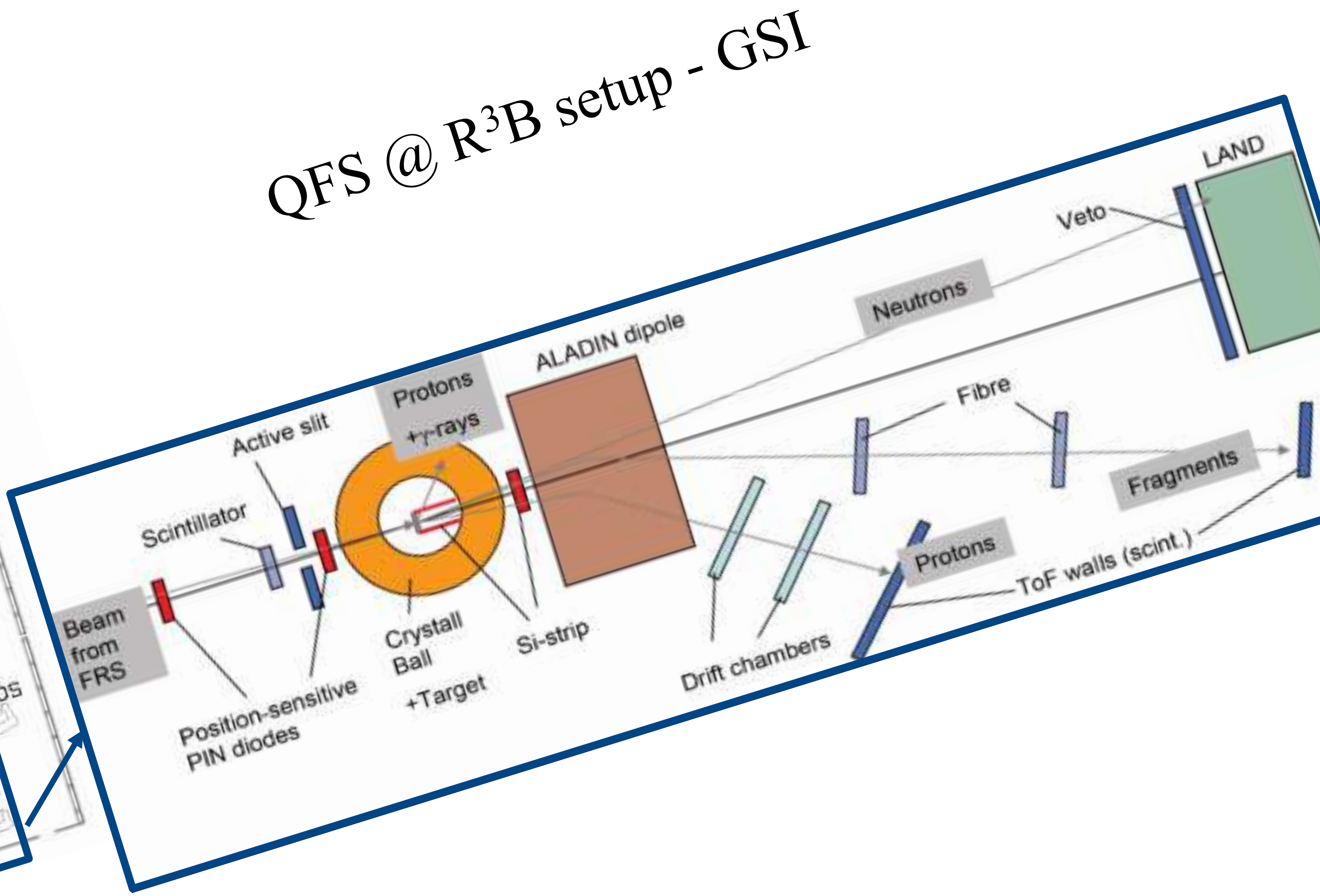
A. Gade, *et.al.* PRC 77, 044306 (2008)



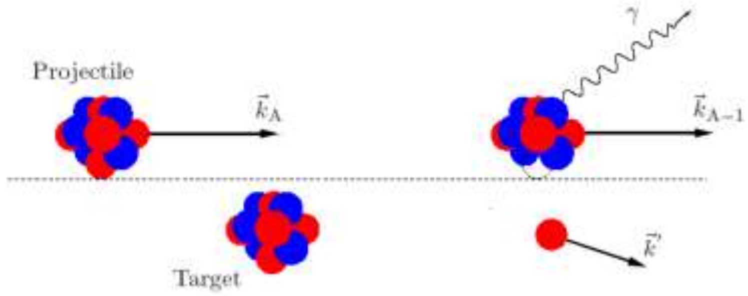
Experimental setup



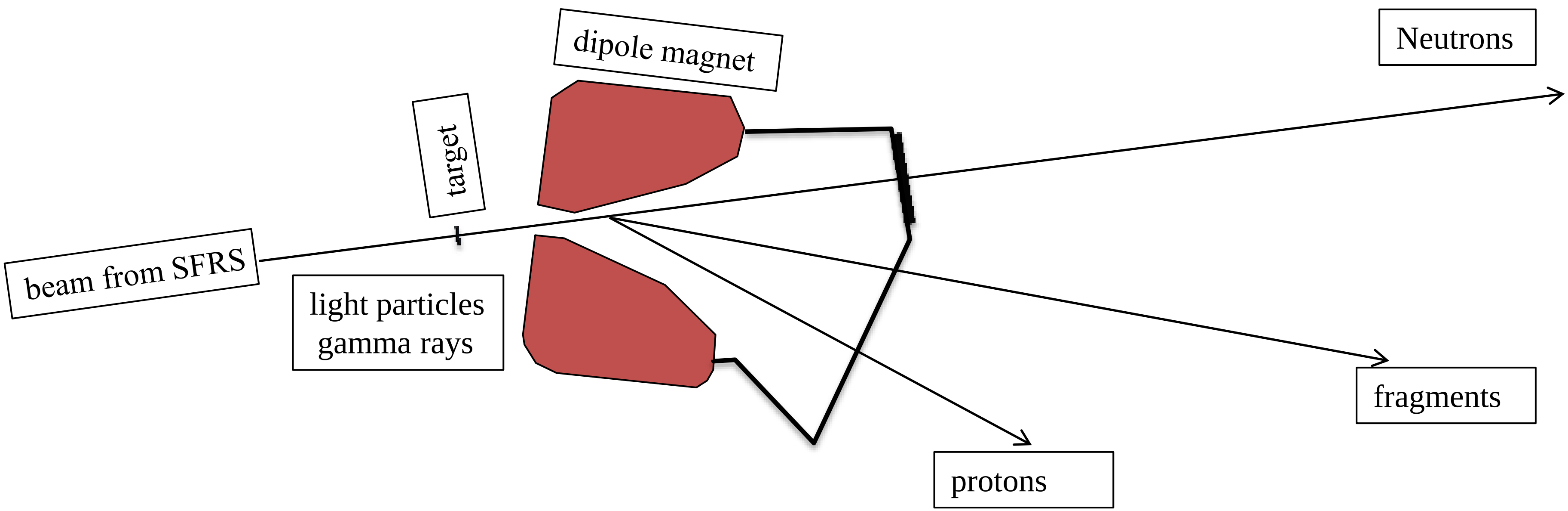
QFS @ R^{3}B setup - GSI



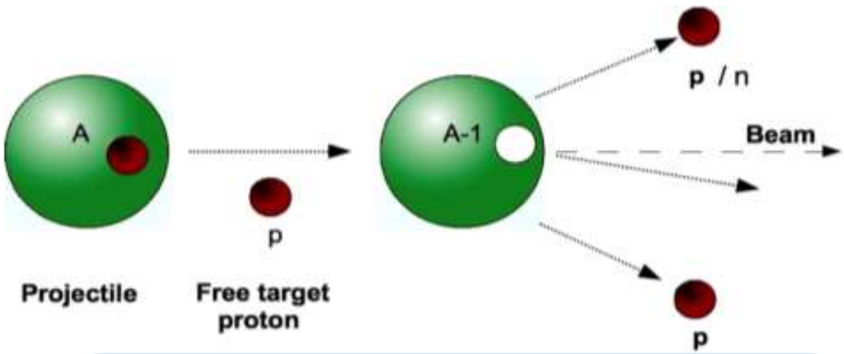
High Energy Branch (HEB)



After the reaction: heavy fragment, neutrons, protons, gammas
Aim: measure all reaction products

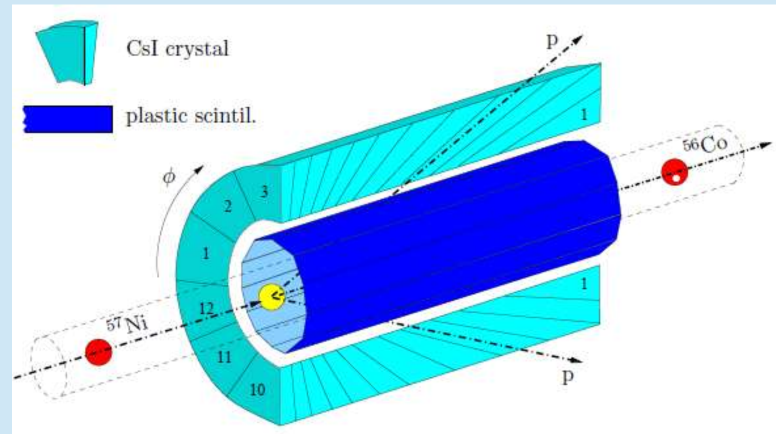


Target recoil detection setup

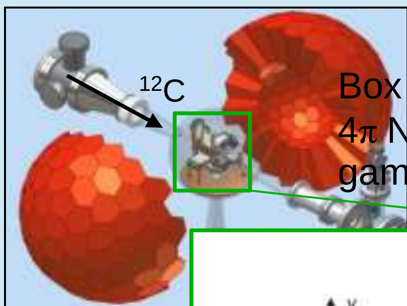


2005

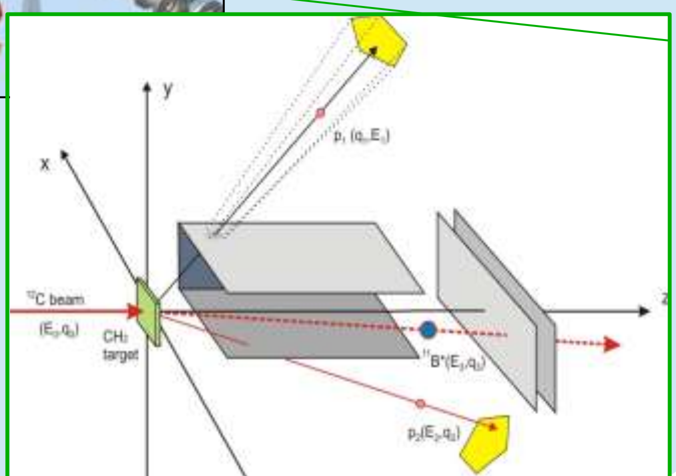
Plastic paddles for proton trigger
4π CsI crystals for gammas and angular measurements of protons and neutrons

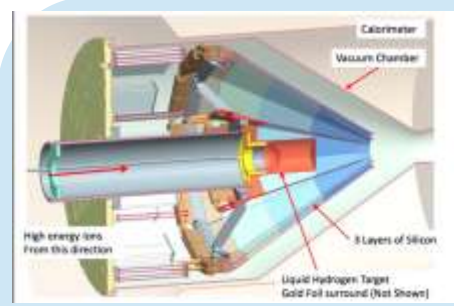


2007-2010



Box of DSSDs for protons
4π NaI crystals,
gammas, protons, neutrons

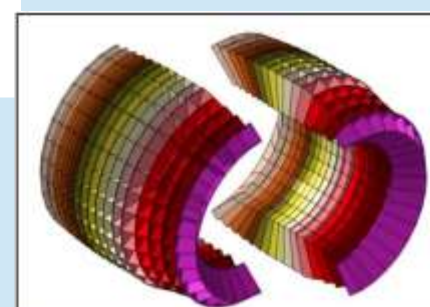




Si Tracker

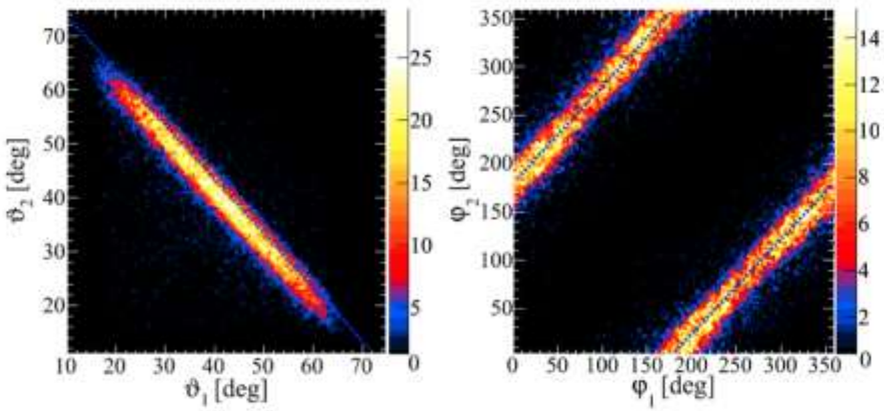
Future setup

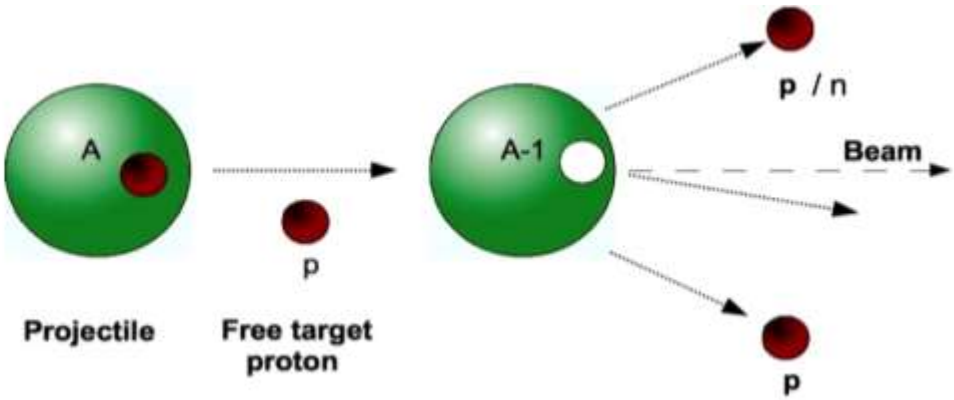
CALIFA



Quasi-free scattering from ^{12}C a Benchmark experiment

Strong angular correlations of the two nucleons

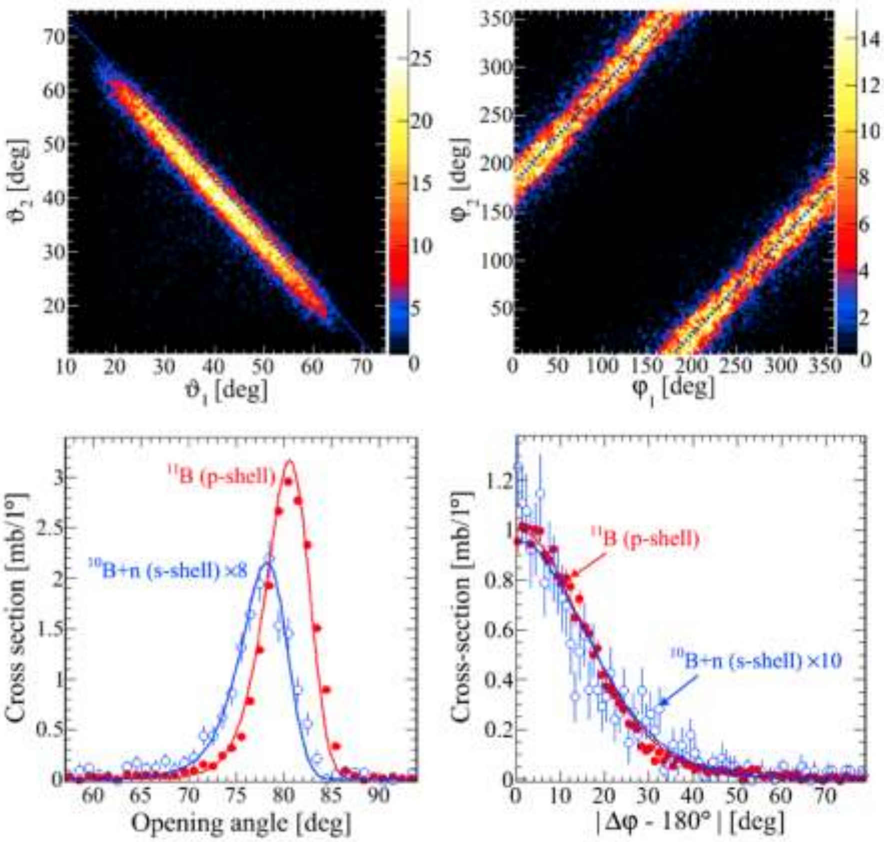




Analysis by V. Panin

Quasi-free scattering from ^{12}C a Benchmark experiment

Kinematics are particularly important!



Analysis by V. Panin

Quasi-free scattering from ^{12}C
a Benchmark experiment

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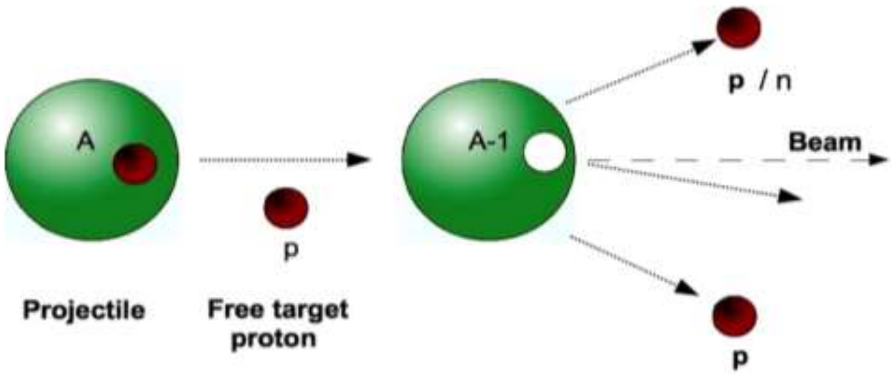

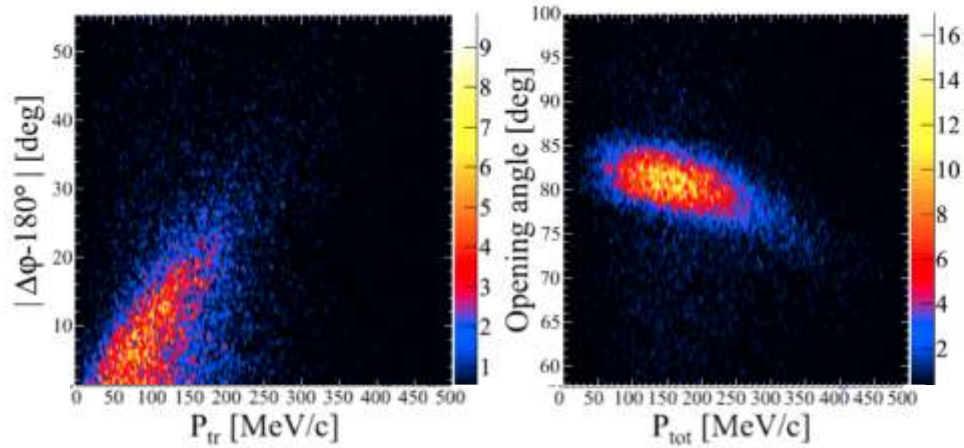

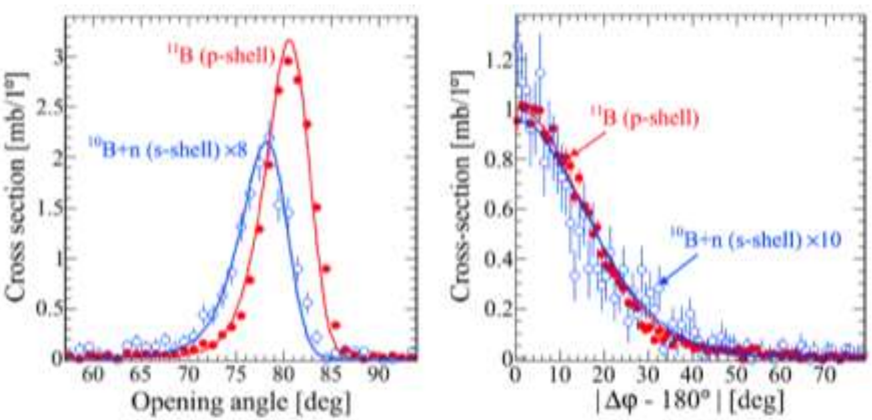

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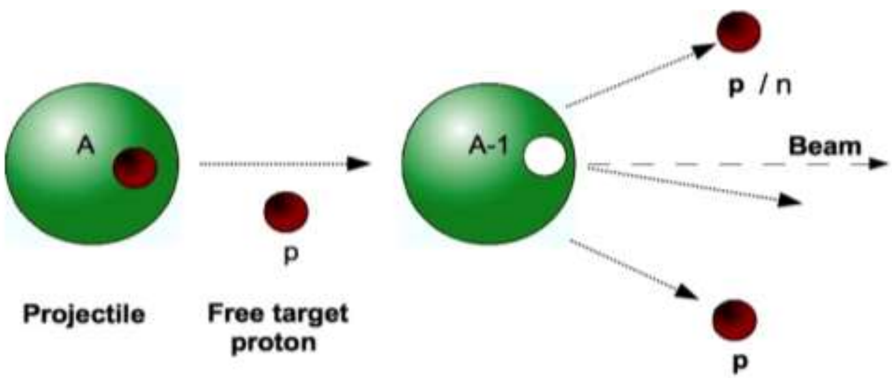
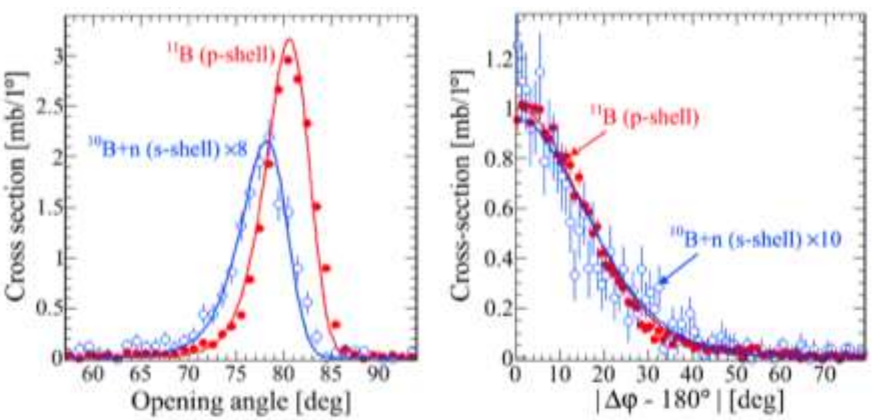
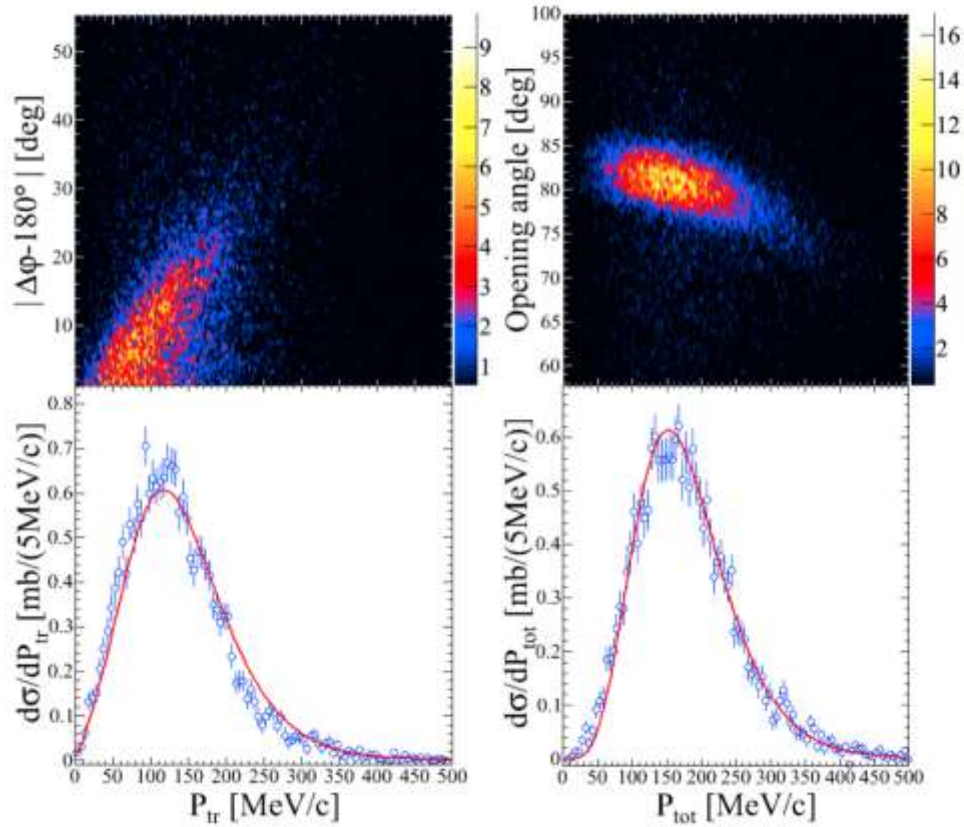






Analysis by V. Panin

Calculations by C. Bertulani (solid line)

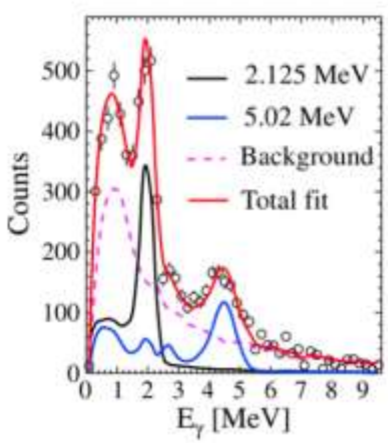
$^{12}C(p,2p)^{11}B$

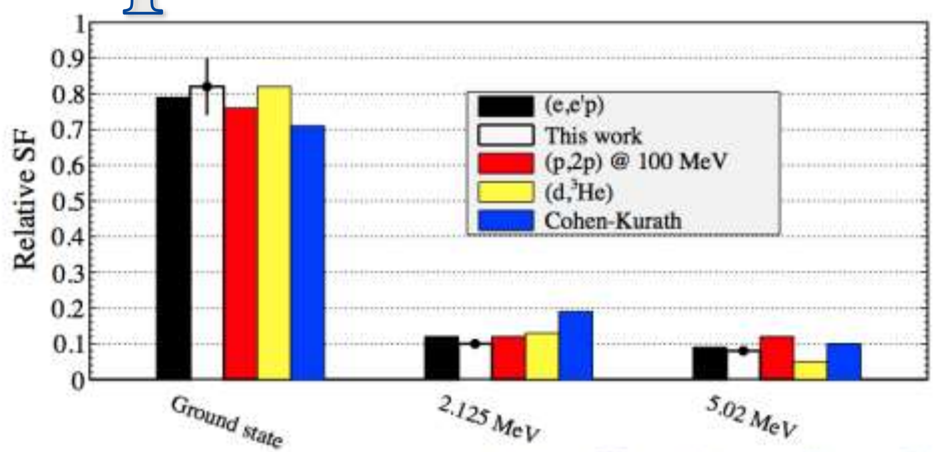
Spectroscopy of $0p$-hole residual states in ^{11}B from $^{12}C(p,2p)^{11}B$ reaction

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

E_x [MeV], J^π	σ(exp), mb	σ(s.p.), mb	S(exp)	$S(e,e'p)$[St]	$S(p,2p)$	$S(d,^3He)$
0.0 (G.S.), $3/2^-$	16.4(18)	7.5	2.18(23) [0.82]	1.72(11) [0.79]	2.02 [0.76]	1.72 [0.82]
2.125, $1/2^-$	2.0(2)	7.4	0.27(3) [0.10]	0.26(2) [0.12]	0.33 [0.12]	0.27 [0.13]
5.02, $3/2^-$	1.6(2)	7.2	0.22(3) [0.08]	0.20(2) [0.09]	0.33 [0.12]	0.11 [0.5]
Total:	20.0(2.2)		2.67(29) [1.00]	2.18(15) [1.00]	2.68 [1.00]	2.1 [1.00]

In Preparation





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

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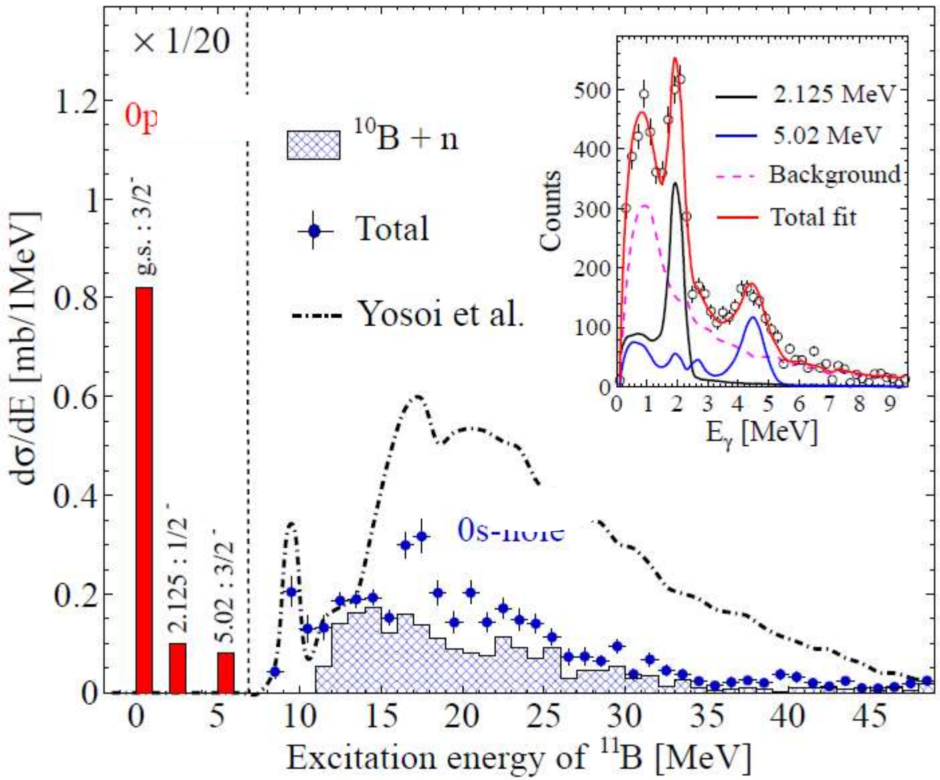
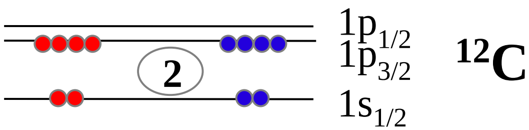


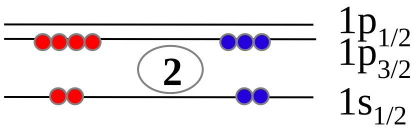


$$M_{inv}^2 = \mathbf{P}^2 = E_{tot}^2 - \vec{P}_{tot}^2 = \left(\sum_j^N E_j\right)^2 - \left(\sum_j^N \vec{p}_j\right)^2,$$

$$E^* = \sqrt{\sum_j^N m_j^2 + \sum_{j \neq k}^N \gamma_j \gamma_k m_j m_k (1 - \beta_j \beta_k cos\vartheta_{jk})} - M_0.$$

Analysis by V. Panin

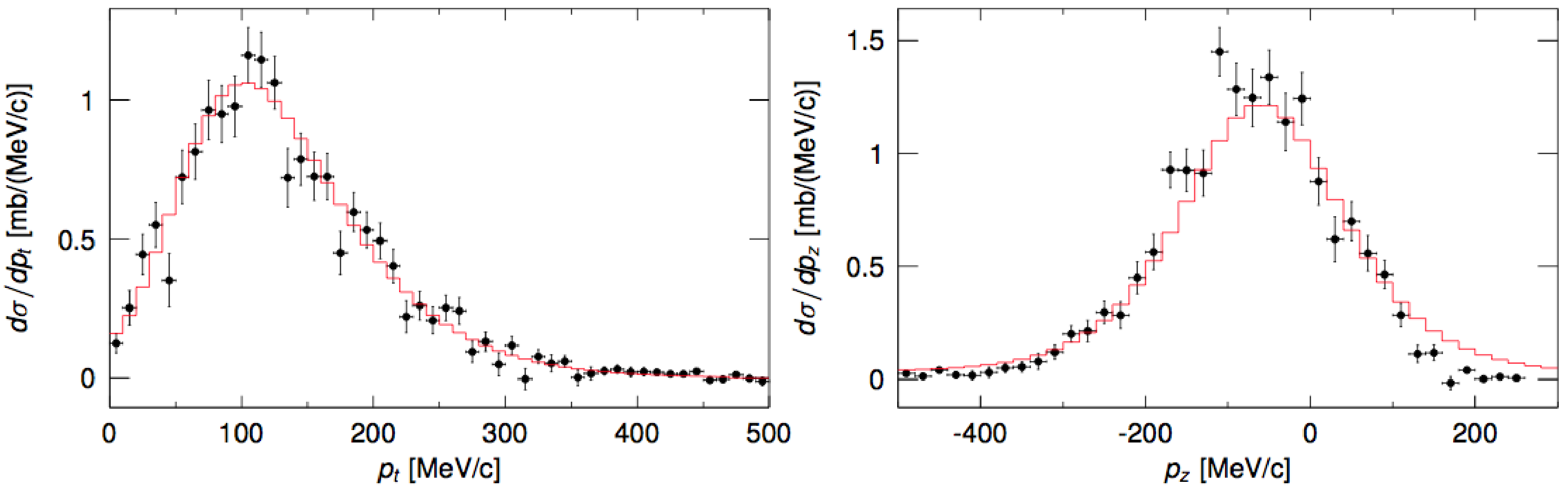
$^{11}C(p,2p)^{10}B$ (inclusive)



^{11}C

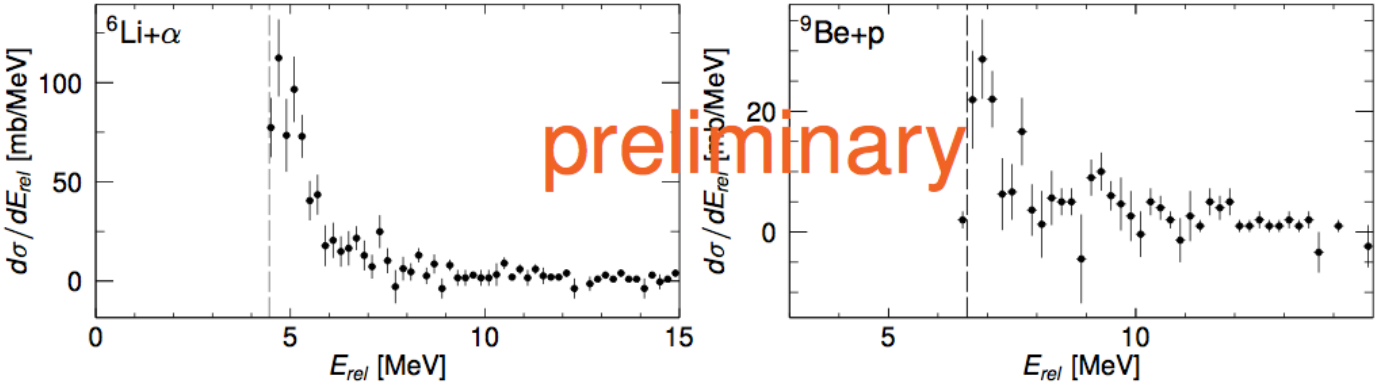
- comparison to DWIA

Reaction	σ_{exp} [mb]	σ_{th} [mb]	σ_{sp} [mb]	S	R_S
$^{11}C(p,2p)^{10}B$	17.3(8)	32.0	8.0	2.16(10)	0.53(2)

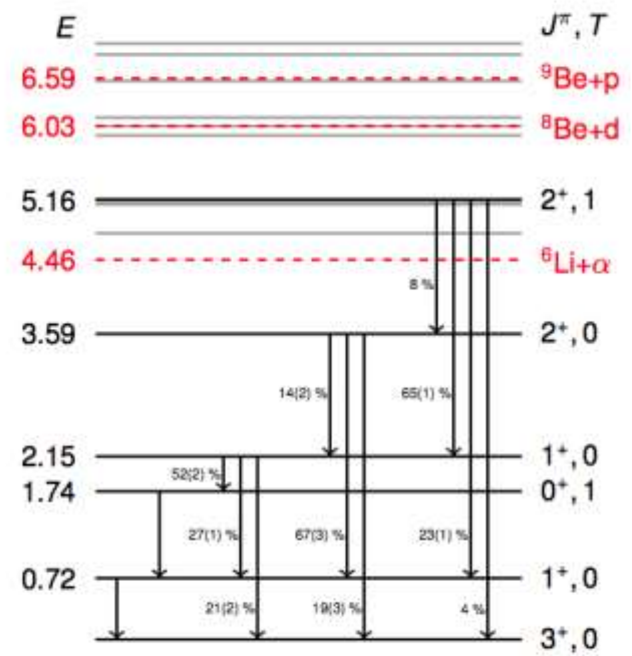


Analysis by M. Holl

$^{11}C(p,2p)^{10}B^* \rightarrow {}^9Be+p, {}^6Li+\alpha$ ...

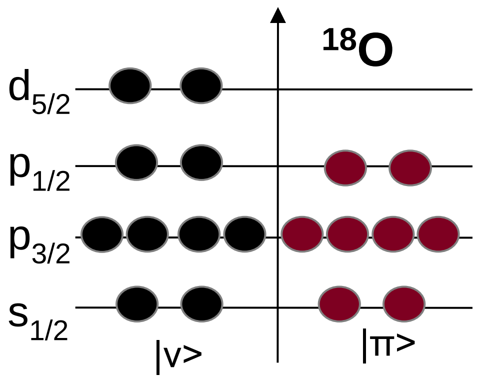


Channel	σ [mb]
$^6Li + \alpha$	4.2(3)
$^9Be + p$	1.2(2)

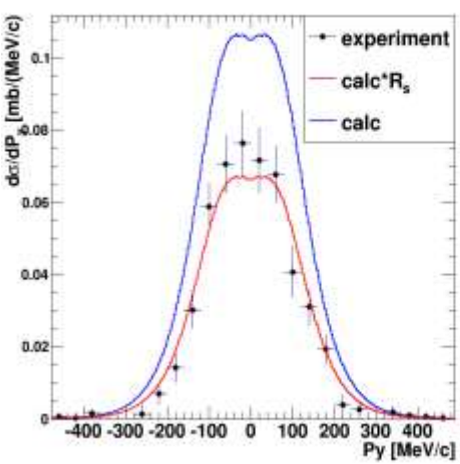


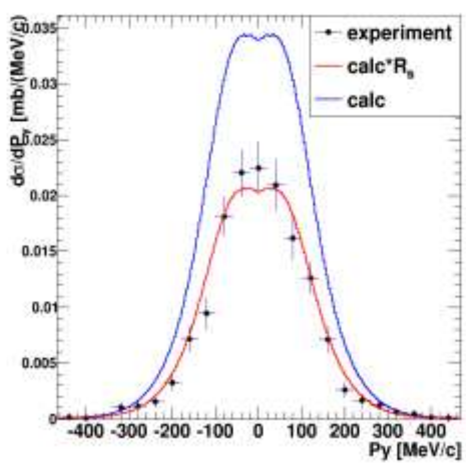
Analysis by M. Holl

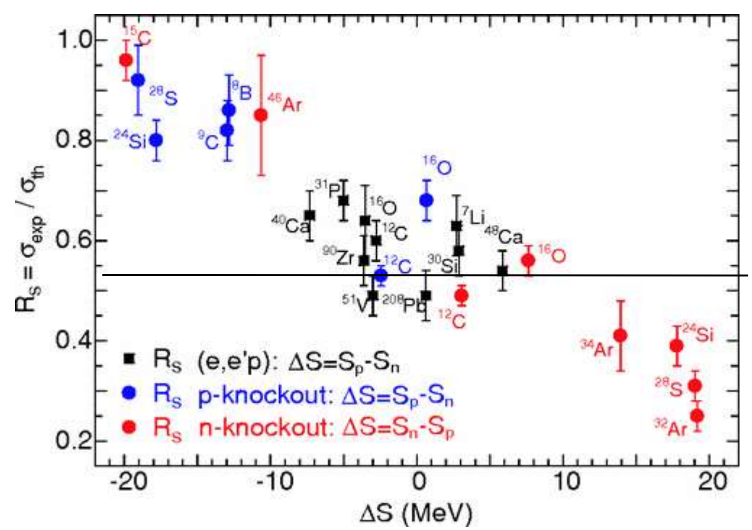
$^{16}O(p,2p)^{15}N$, $^{17}O(p,2p)^{16}N$, $^{18}O(p,2p)^{17}N$



isotope	^{16}O	^{17}O	^{18}O	^{15}N	^{16}N	^{17}N
Sp/n[MeV]	12/16	14/4	16/8	10/11	12/3	13/6







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

Inclusive (p,2p) and (p,pn) cross sections for $^{67-72}$Ni crossing the N=40

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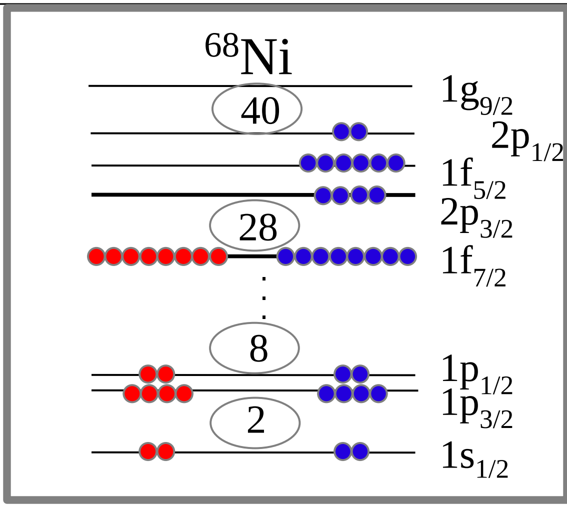
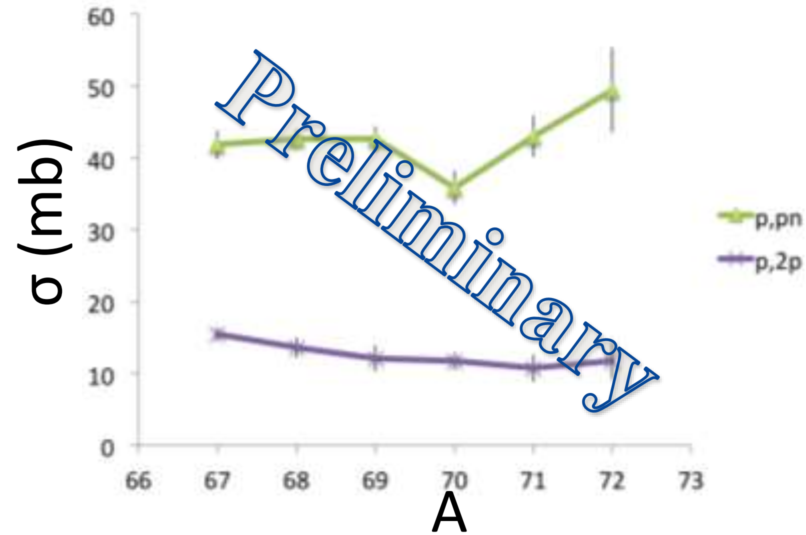
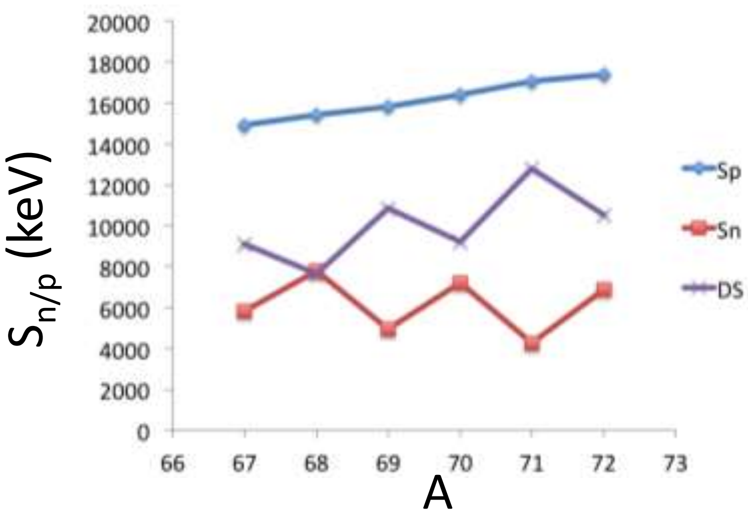
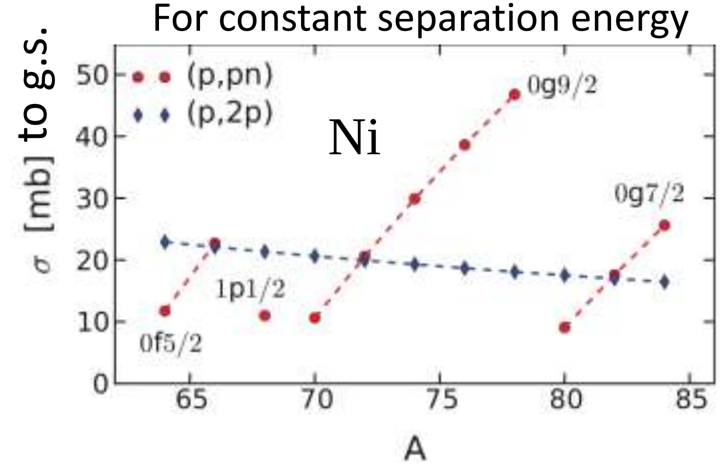






For constant separation energy



PRC 88, 064610 (2013)

But… the analysis so far includes only angular correlations between the protons not their full momentum measurement…

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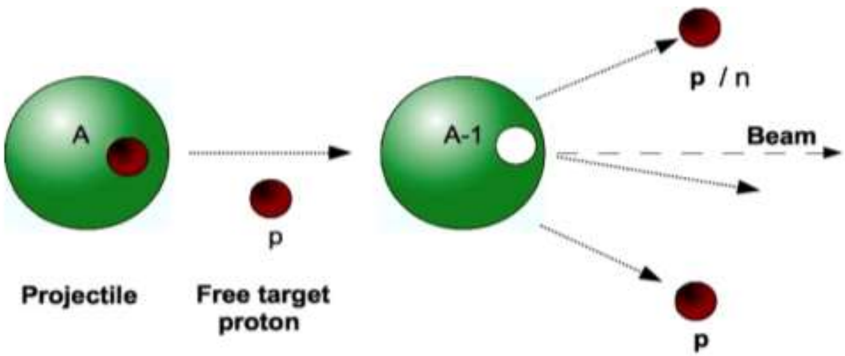
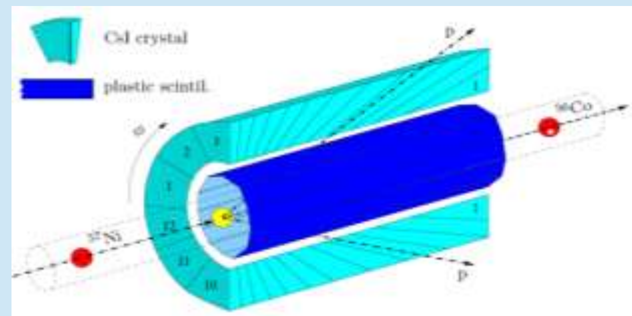
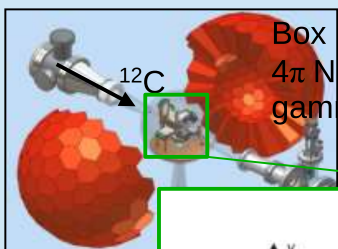
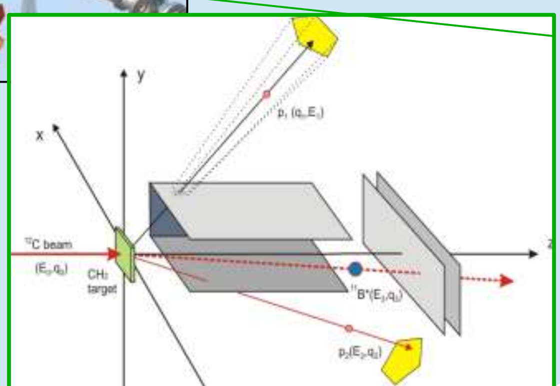


2005
Plastic paddles for proton trigger
4π CsI crystals for gammas and angular measurements of protons and neutrons



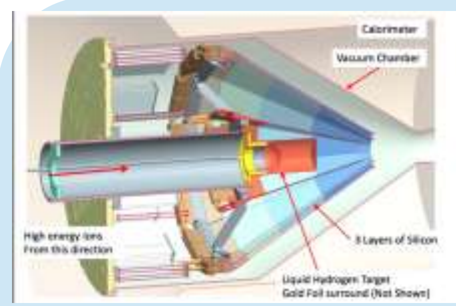
2007-2010
Box of DSSDs for protons
4π NaI crystals,
gammas, protons, neutrons



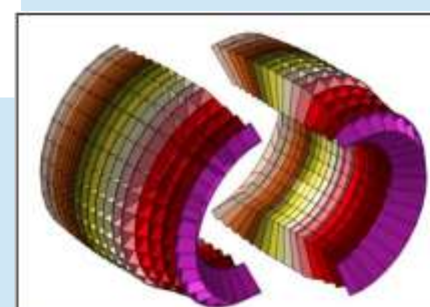


Future setup

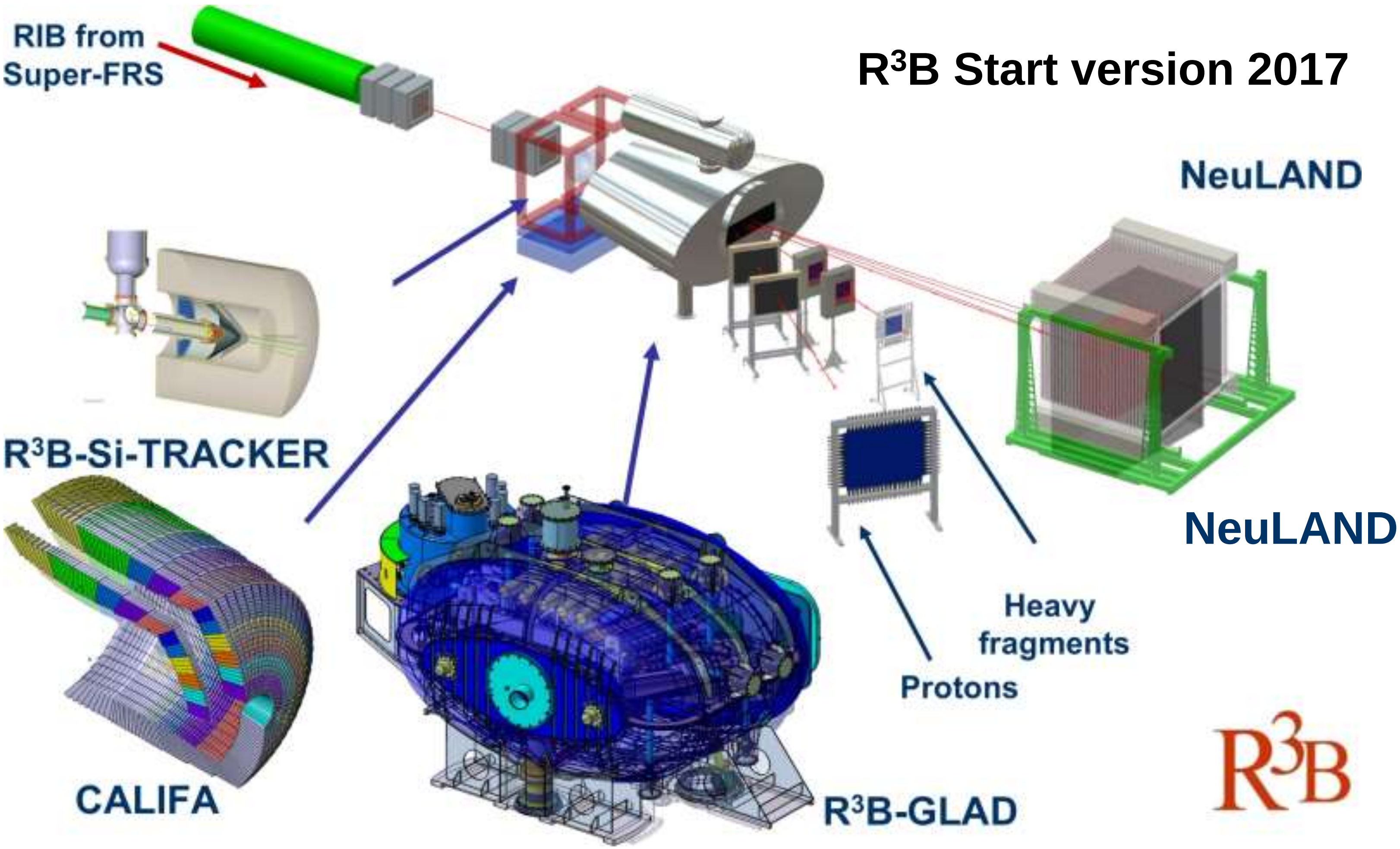
CALIFA



Si Tracker



R³B - Reactions with Relativistic Radioactive Beams



Large-acceptance superconducting dipole magnet GLAD

Technical drawing of the GLAD magnet.

Cold mass built at the CEA Saclay (France).

H. Simon

Bend and momentum analyze the rigid beams while letting the decaying neutrons fly through with large acceptance

Magnet parameters:

- Large vertical gap ± 80 mrad
- High integrated field of 4.5 Tm
- Fringe field at the target position less than 20 mT
- Operational temperature 4.6 K
- The overall size of the conical cryostat: 3.5 m long, 3.8 m high and 7 m wide.

High-resolution neutron time-of-flight spectrometer NeuLAND

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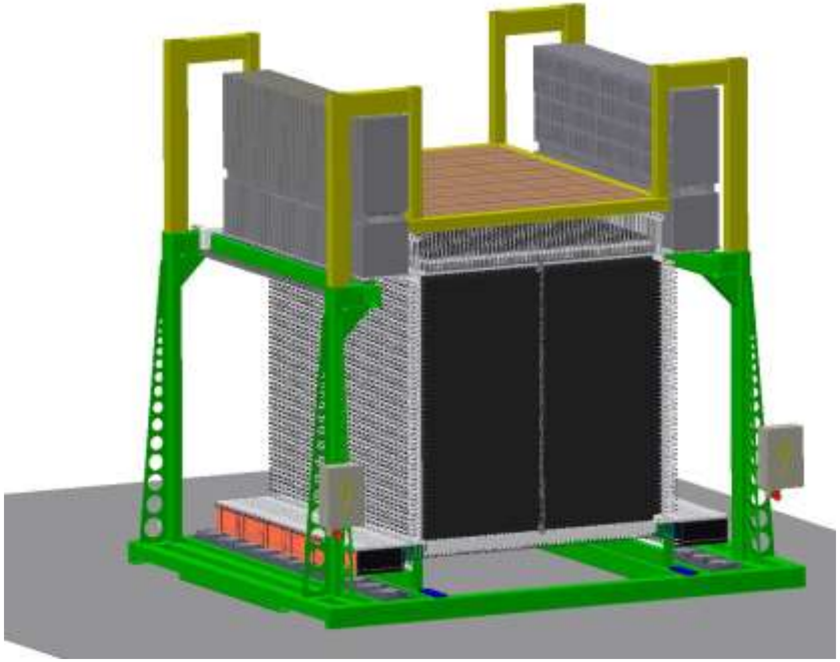
Detector parameters:

- Full active detector using organic scintillator
- Face size 250x250 cm^2, active depth 300 cm
- 3000 scintillator bars
- 6000 photomultiplier and readout channels
- Modular design.

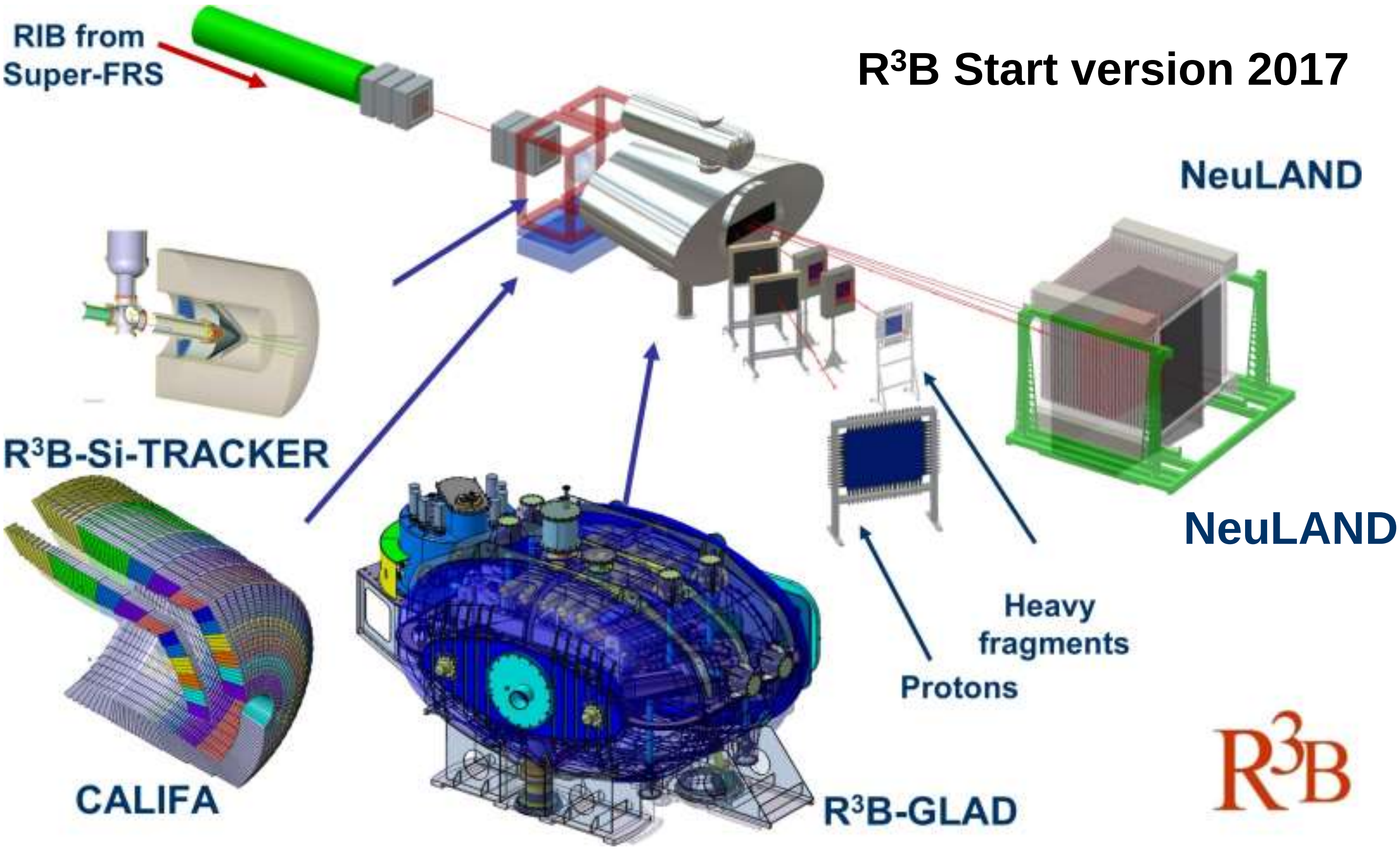
Performance goals:

- >90% efficiency for 0.2-1 GeV neutrons
- Multi-hit capability for up to 5 neutrons
- <150 ps time resolution
- 20 keV excitation-energy resolution at 100 keV above neutron threshold.

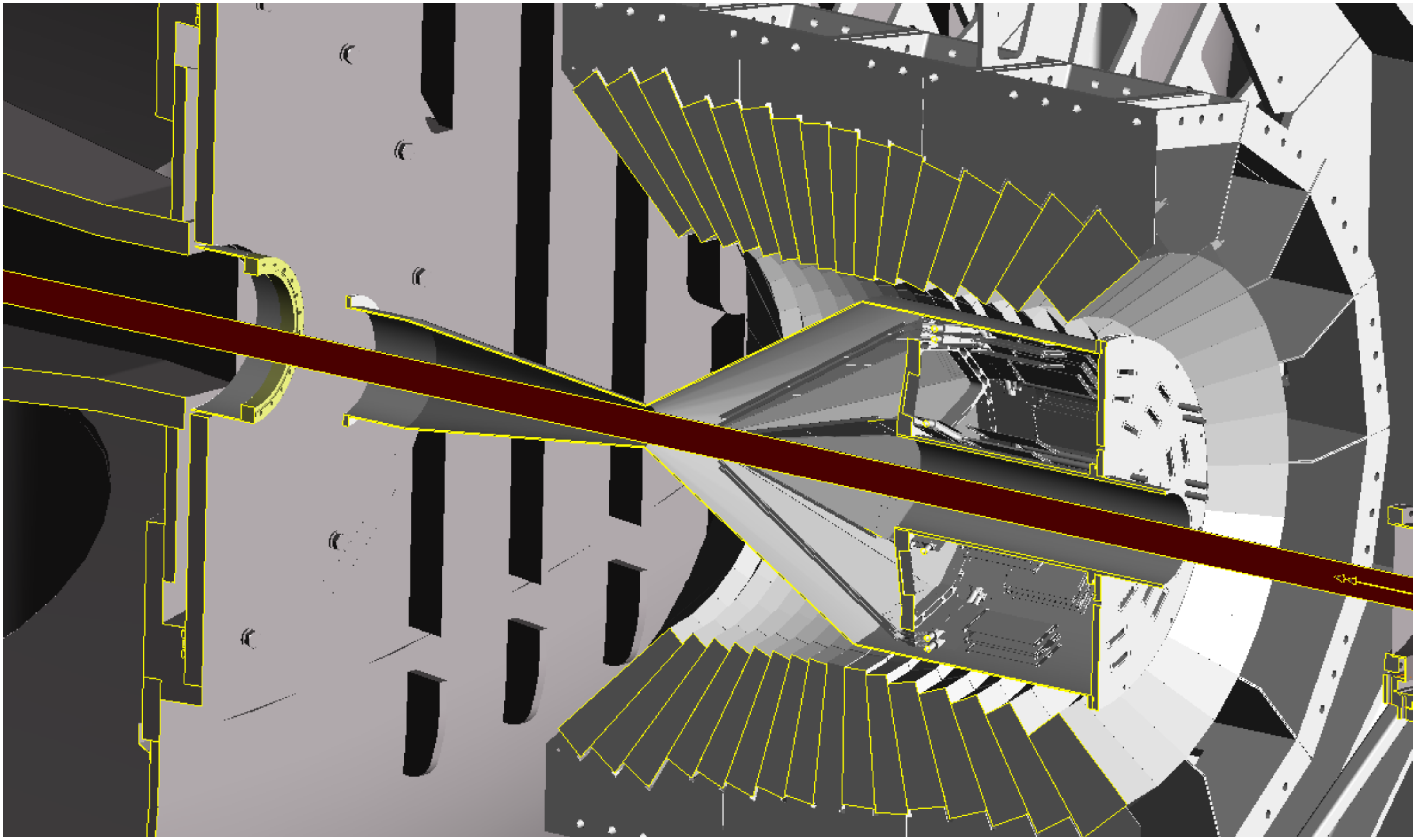


K. Boretzky

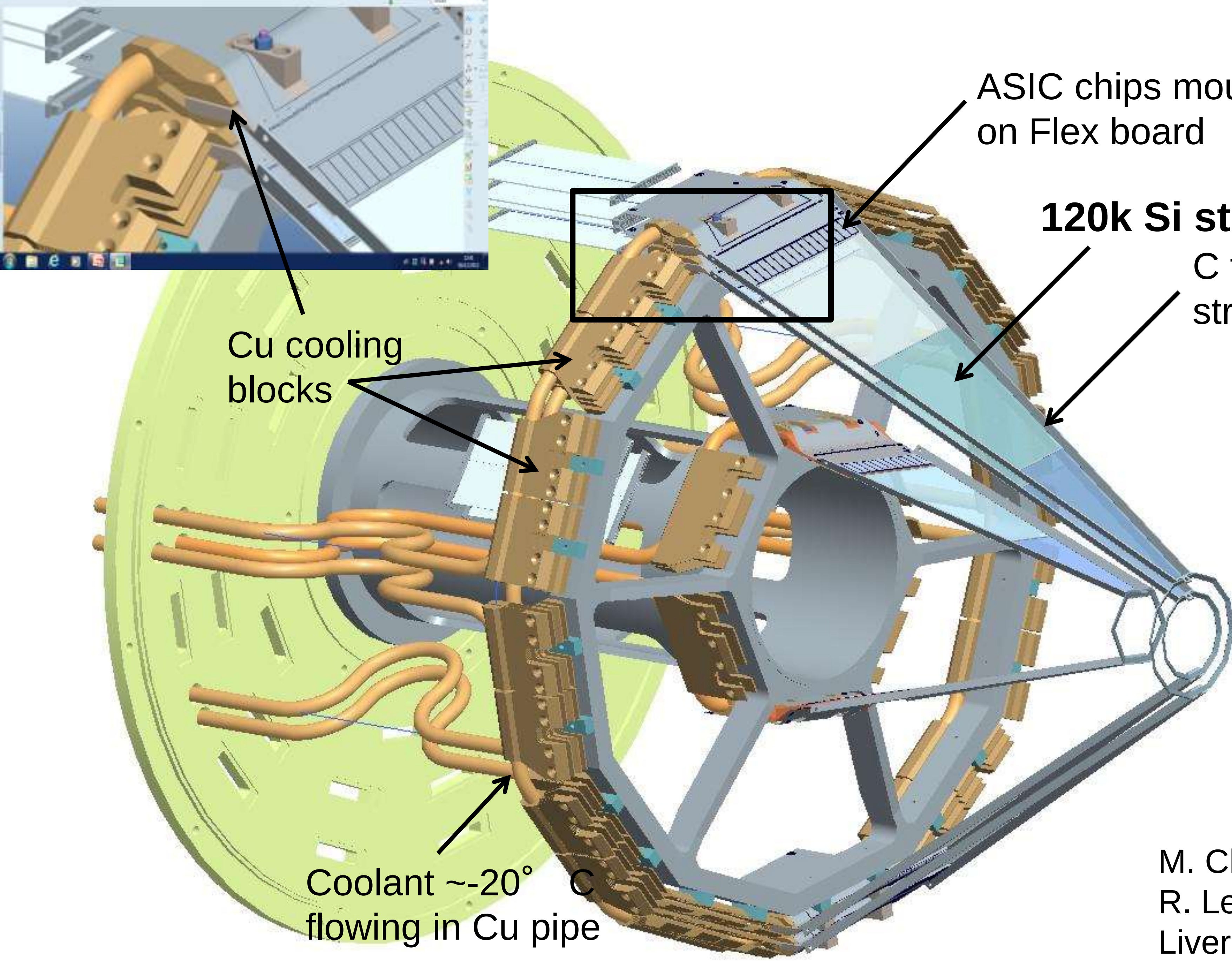
R^{3}B - Reactions with Relativistic Radioactive Beams



Target Recoil Detector: CALIFA Barrel and Silicon Tracker



Alan Grant,Daresbury



M. Chartier, R. Lemon, Liverpool, Daresbury

CALIFA γ-ray Calorimeter, Spectrometer, charged particle detector

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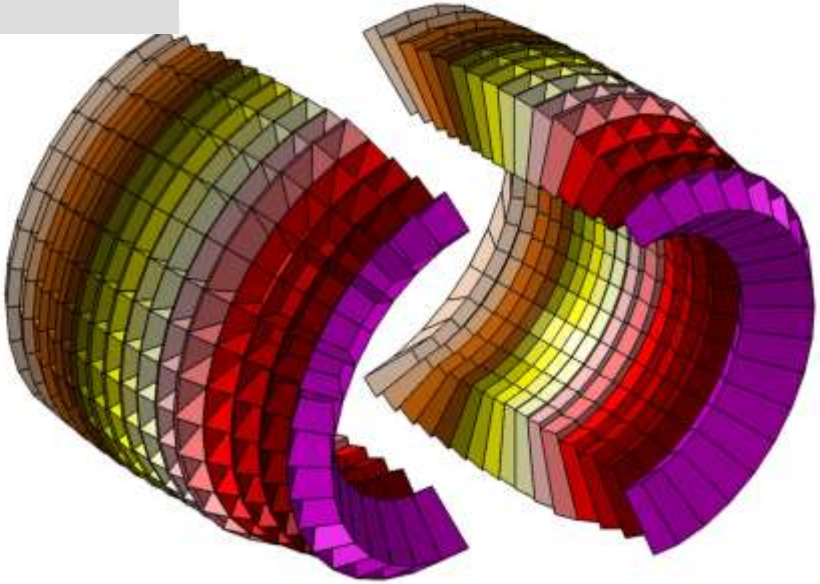
→ **large dynamic range (γ 100 keV - 20 MeV and p 1-320 MeV)**

Calorimetrer	Intrinsic photopeak efficiency	40% (up to Eg=15 MeV projectile frame)
	Gamma sum energy resolution $\Delta(E_\gamma sum)/<(E_\gamma sum)>$	< 10% for 5 γ rays of 3 MeV
	Calorimeter for high energy Light charged particles	Up to 320 MeV in lab system
Spectrometer	Gamma energy resolution	~5-6% (FWHM at Eγ=1 MeV)
	Light charged particles resolution	~2%
	Proton - γ ray separation	For 1 to 30 MeV

Inner radius	30 cm
N of crystals	1952
Crystal geom.	11
Crystal Volume/ weight	285 000 cm^3/ 1300 kg



D. Cortina

First in-beam test of four NeuLAND double planes, two CALIFA pedals and two ladders from the Si tracker successfully completed in Cave C last week!!!

Near future – Completion of detector construction

- Installing GLAD superconducting dipole magnet in Cave C by end of this year
  - Enables bending of rigid beams of 1GeV/nucleon for the first time
- Complete Si tracker detector in Q1 2016
  - Unprecedented angular resolution for the outgoing protons following a QFS reaction and precise reaction-vertex reconstruction
- Large part of the CALIFA calorimeter barrel completed by 2016
  - Total energy measurement of the outgoing protons following a QFS reaction for the first time
- Complete NeuLAND detector by 2016
  - Unprecedented multi-neutron detection efficiency will allow for investigation of up to 5 neutron decays for the first time

Near future – Unique QFS physics program

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- The use of higher energy beams
  - enables studies of heavier systems free of charge state contaminations
  - provides sufficient momentum transfer to study short-range correlations in inverse kinematics of stable and unstable nuclei for the first time

- The target recoil system
  - enables precise and kinematically complete measurement of the target recoil light fragments scattered at large angles for the first time

→ **Unique physics program with the current secondary-beam intensities and precision measurements with stable nuclei**

Summary

- Quasi-free scattering
  - QFS is successfully applied in inverse kinematics for spectroscopic studies in R^3B
  - Rich data sets covering a wide range of nuclei are under analysis
  - Reaction theory by C.A. Bertulani provides a good understanding of the data
  - Rich physics program: shell structure, cluster structure, unbound nuclei, N-N correlations (SRC)

- R^3B setup ideal for such investigations

- Upgraded setup in the near future opens up the way for a unique physics program with high-resolution high-selectivity studies

Thank you for your attention!

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R3B Collaboration

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

Thank you for your attention!

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.t; 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.;

Motivation

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SRC in general

- Learn about NN force at short distances
- Nuclear structure
- In-medium modifications
  - EMC effect

SRC in inverse kinematics with radioactive beams allows, in addition, to access a

- wide range of A + Isospin study
  - What is the number and isospin structure of NN - SRC in very asymmetric nuclei (N≠Z) ?
  - Is momentum of the nucleons in minority higher? (E. Piasetzky talk)
- complete (and redundant) kinematical measurement
  - including the A-2 residue and its possible evaporated particles
  - measure the CM motion of the NN - SRC pair

$^{9\text{-}16}C$ T. Kobayashi et al. NPA 805 (2008) 431c

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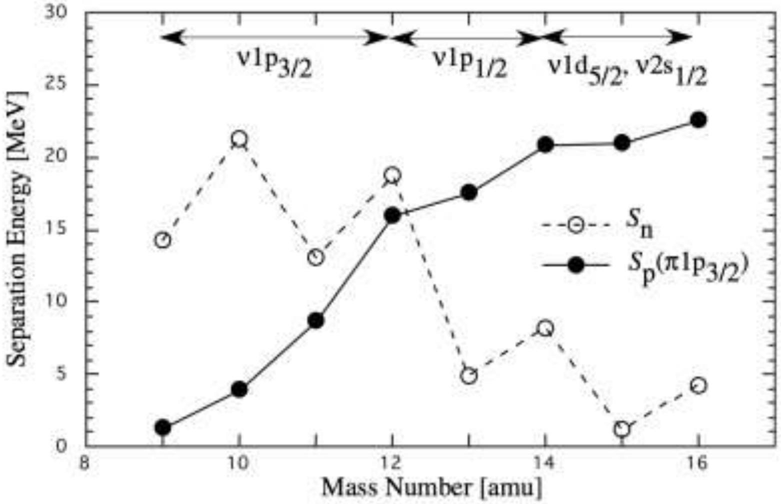
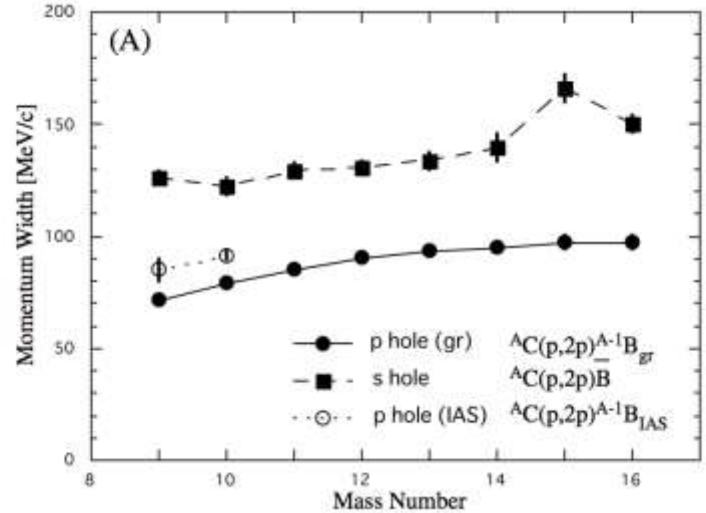
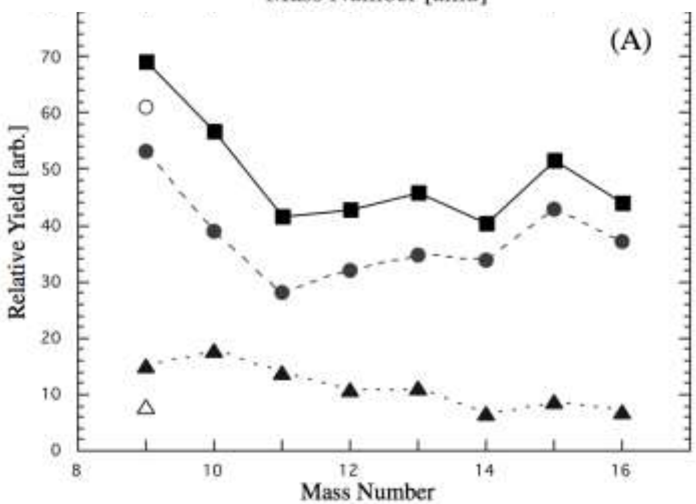
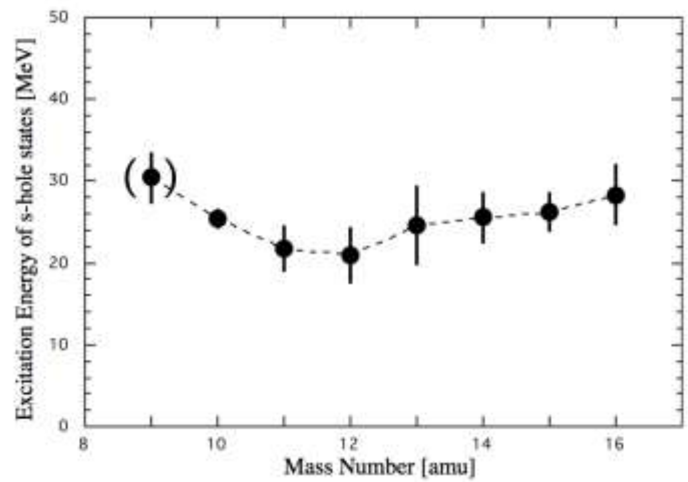








Short-Range Correlations (SRC)

- 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

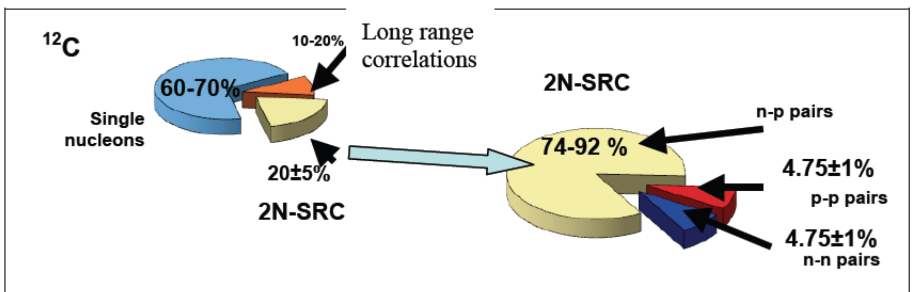
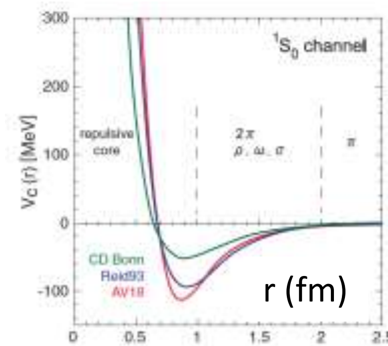
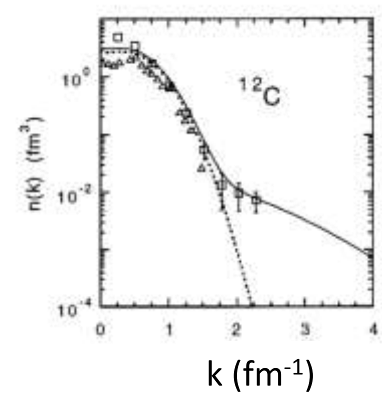


Figure from O. Hen *et al.* “A proposal to Jefferson Lab PAC 38, Aug. 2011”

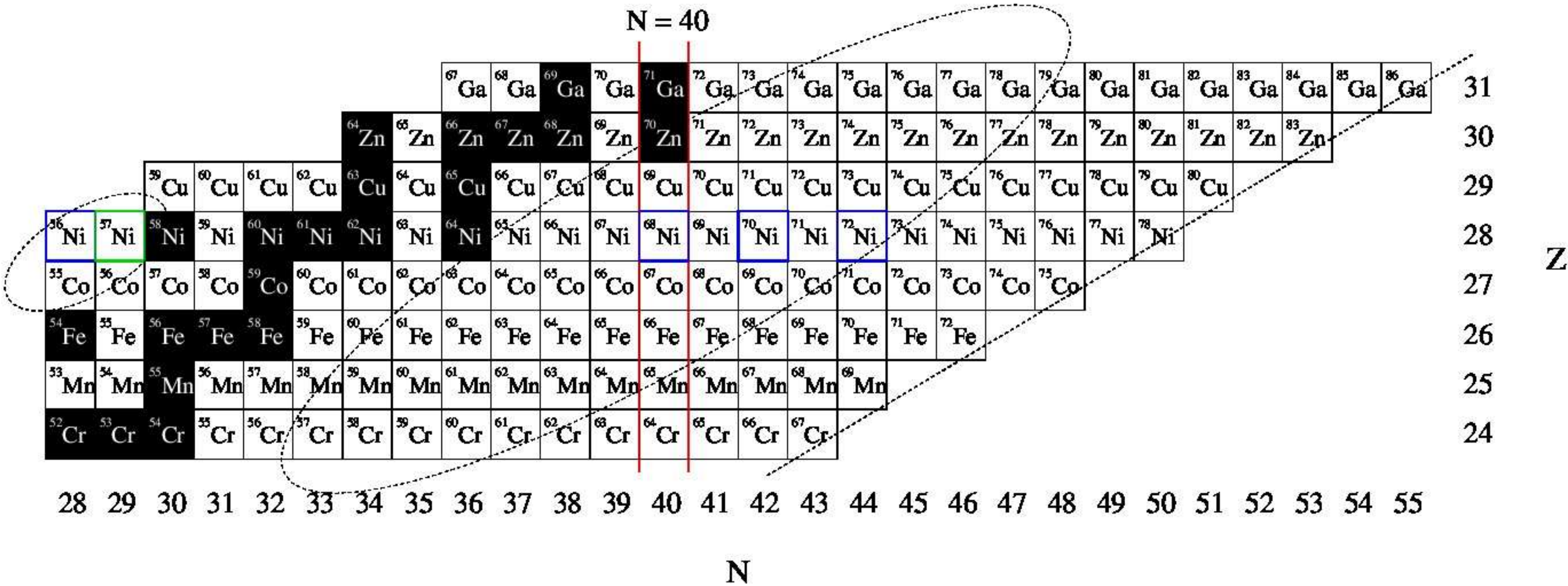




SRC arises from the repulsive core of the NN interaction

➢ Responsible for the high momentum component of the nuclear wavefunction

C. Ciofi degli Atti PRC 53 (1996) 1689


N = 40
67Ga 68Ga 69Ga 70Ga 71Ga 72Ga 73Ga 74Ga 75Ga 76Ga 77Ga 78Ga 79Ga 80Ga 81Ga 82Ga 83Ga 84Ga 85Ga 86Ga 31
64Zn 65Zn 66Zn 67Zn 68Zn 69Zn 70Zn 71Zn 72Zn 73Zn 74Zn 75Zn 76Zn 77Zn 78Zn 79Zn 80Zn 81Zn 82Zn 83Zn 30
59Cu 60Cu 61Cu 62Cu 63Cu 64Cu 65Cu 66Cu 67Cu 68Cu 69Cu 70Cu 71Cu 72Cu 73Cu 74Cu 75Cu 76Cu 77Cu 78Cu 79Cu 80Cu 29
56Ni 57Ni 58Ni 59Ni 60Ni 61Ni 62Ni 63Ni 64Ni 65Ni 66Ni 67Ni 68Ni 69Ni 70Ni 71Ni 72Ni 73Ni 74Ni 75Ni 76Ni 77Ni 78Ni 28
55Co 56Co 57Co 58Co 59Co 60Co 61Co 62Co 63Co 64Co 65Co 66Co 67Co 68Co 69Co 70Co 71Co 72Co 73Co 74Co 75Co 27
54Fe 55Fe 56Fe 57Fe 58Fe 59Fe 60Fe 61Fe 62Fe 63Fe 64Fe 65Fe 66Fe 67Fe 68Fe 69Fe 70Fe 71Fe 72Fe 26
53Mn 54Mn 55Mn 56Mn 57Mn 58Mn 59Mn 60Mn 61Mn 62Mn 63Mn 64Mn 65Mn 66Mn 67Mn 68Mn 69Mn 25
52Cr 53Cr 54Cr 55Cr 56Cr 57Cr 58Cr 59Cr 60Cr 61Cr 62Cr 63Cr 64Cr 65Cr 66Cr 67Cr 24
Z
28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55
N

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

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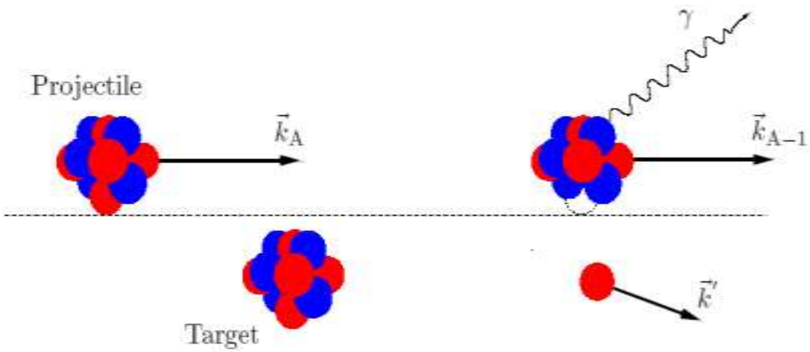
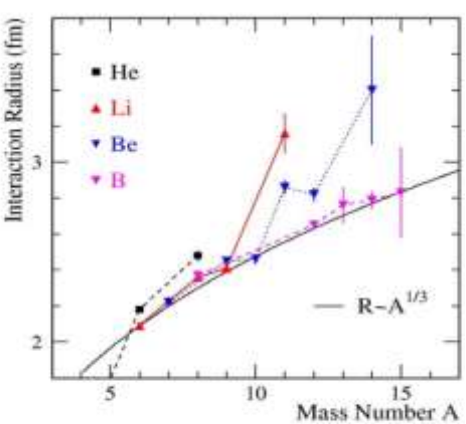
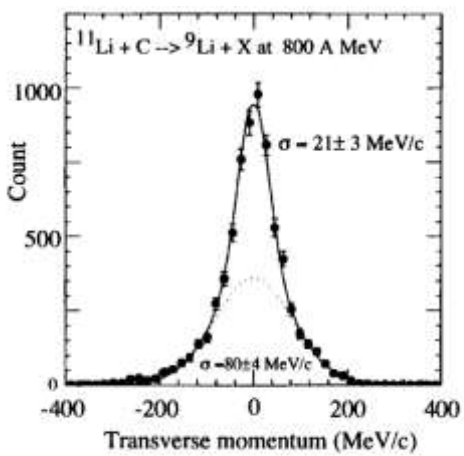


Knockout reactions on light nuclear targets have helped to reveal new quantum phenomena such as the nuclear halo and to map significant changes in the shell structure far from stability e.g. weakening of shell gaps, island of inversion…

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





Interaction cross section → Interaction radii

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

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

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

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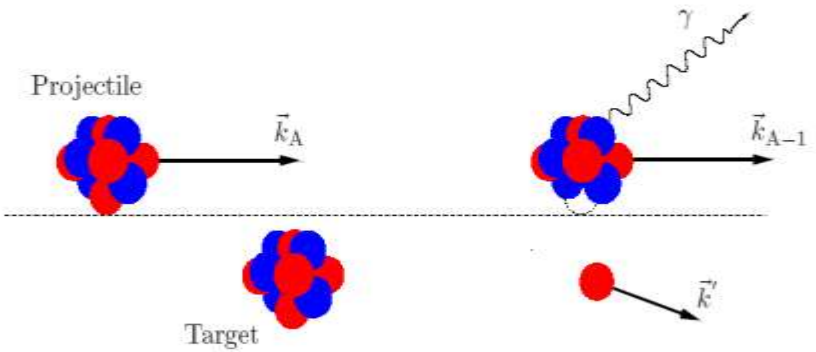

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