IOP Institute of Physics
Nuclear and Particle Physics Divisional Conference (NPPD)
4–7 April 2011, University of Glasgow, UK

Asymmetric Nuclear Matter Explored With Relativistic Radioactive Beams At GSI/FAIR

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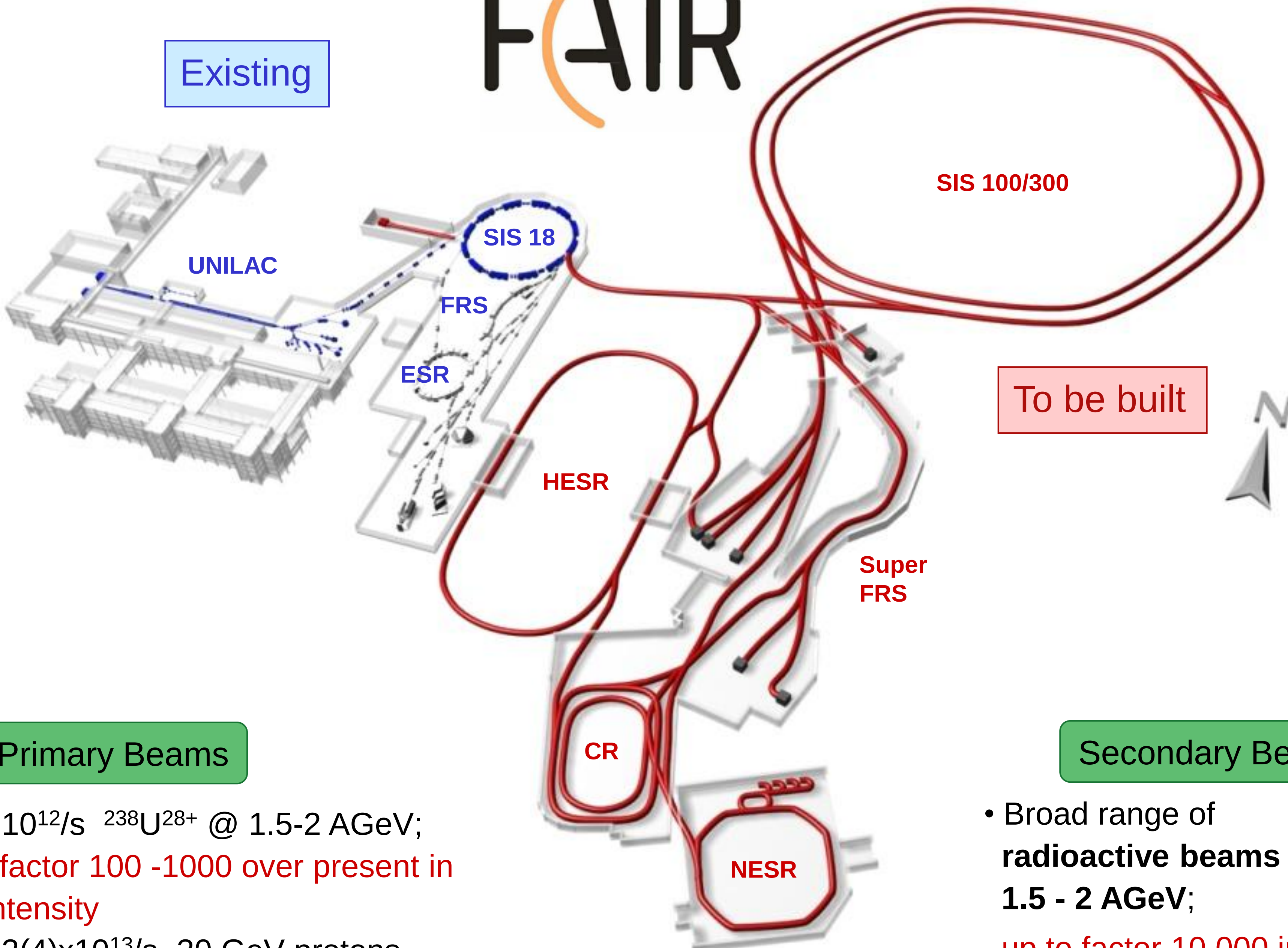
UNIVERSITY OF LIVERPOOL

The Future International Facility FAIR at GSI: Beams of Ions and Antiprotons

FAIR
Facility for Antiproton and Ion Research



Primary Beams

- 10^{12}/s $^{238}U^{28+}$ @ 1.5-2 AGeV; factor 100 -1000 over present in intensity
- 2(4)x10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (-35) AGeV

Secondary Beams

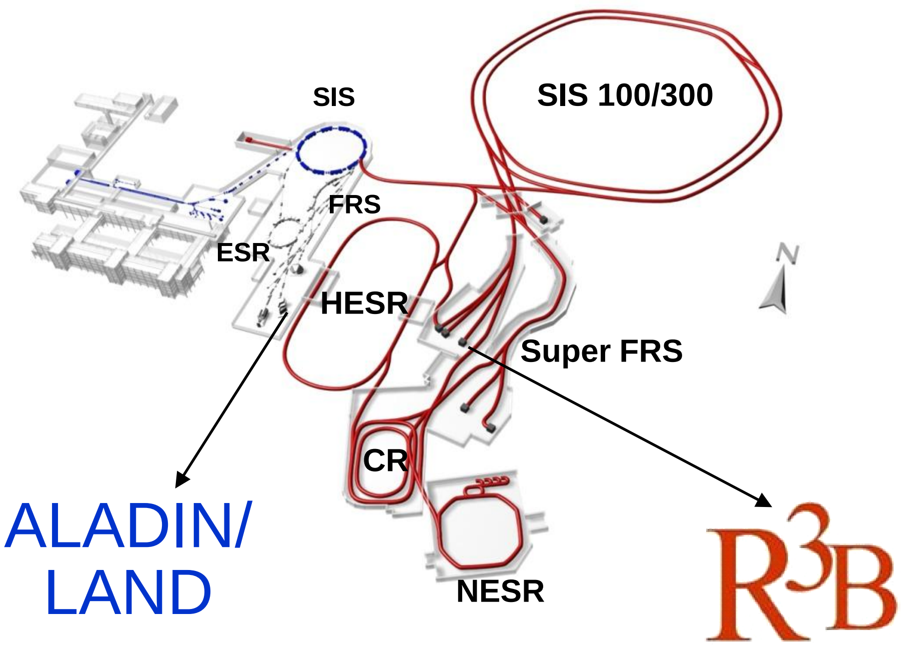
- Broad range of **radioactive beams up to 1.5 - 2 AGeV**; up to factor 10 000 in intensity over present

On-going and future research programme at GSI and FAIR

- How do nucleon-nucleon correlations evolve in isospin-asymmetric nuclei and nuclear matter?

- Hadronic quasifree scattering reactions in inverse kinematics with RIBs at high energy using the ALADIN/LAND setup at GSI

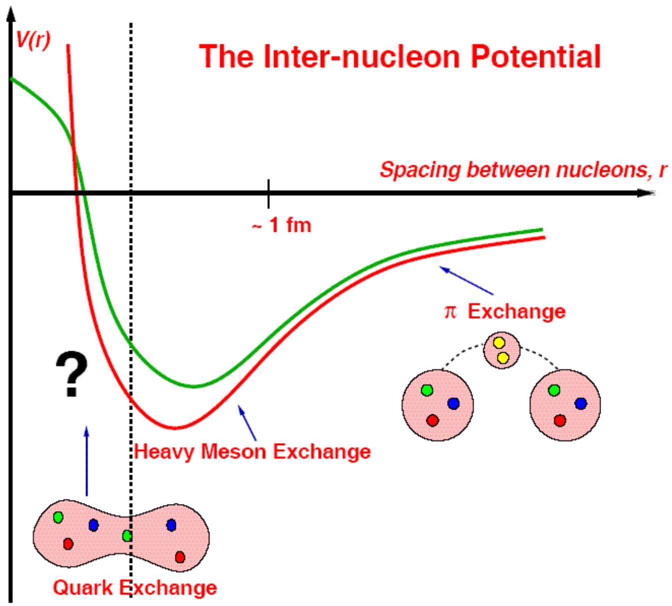
- Future prospects at FAIR with the new R^3B experiment



See also poster by Jonathan Taylor (Liverpool) and talk by Zoe Matthews (Liverpool)

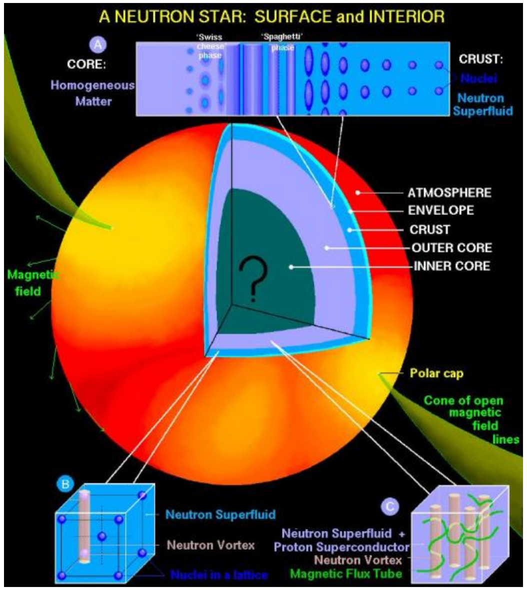
Beyond the Nuclear Mean-Field

Nucleon-Nucleon correlations:
Short-range (SRC)
Tensor
Long-range (LRC)



Modification of NN correlations as a function of density, temperature, isospin asymmetry determine the nature of many-body systems

- Finite nuclei, nuclear structure
- Extended nuclear matter, EOS
- Compact astrophysical object e.g. neutron stars



Very challenging theoretically to incorporate correlations in the nuclear many-body system starting from bare NN interactions

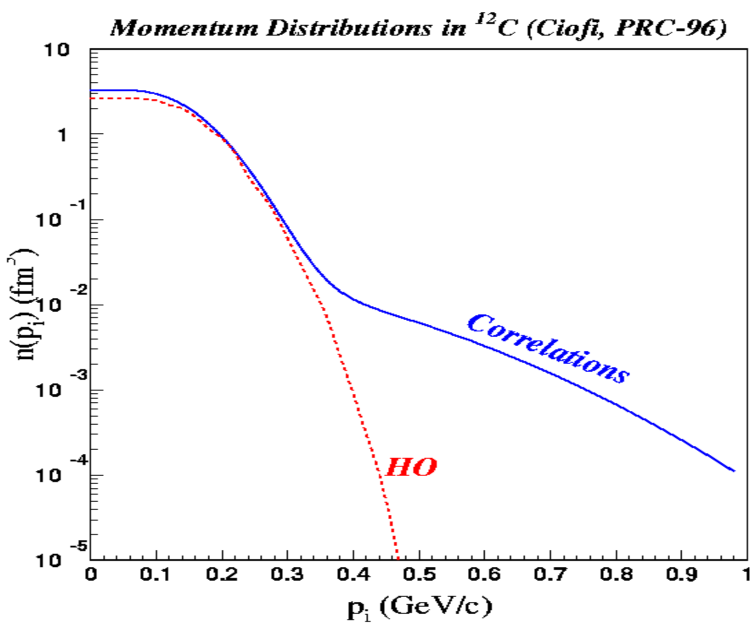
- Experimental studies crucially needed

Correlations in (Near-) Symmetric Nuclei

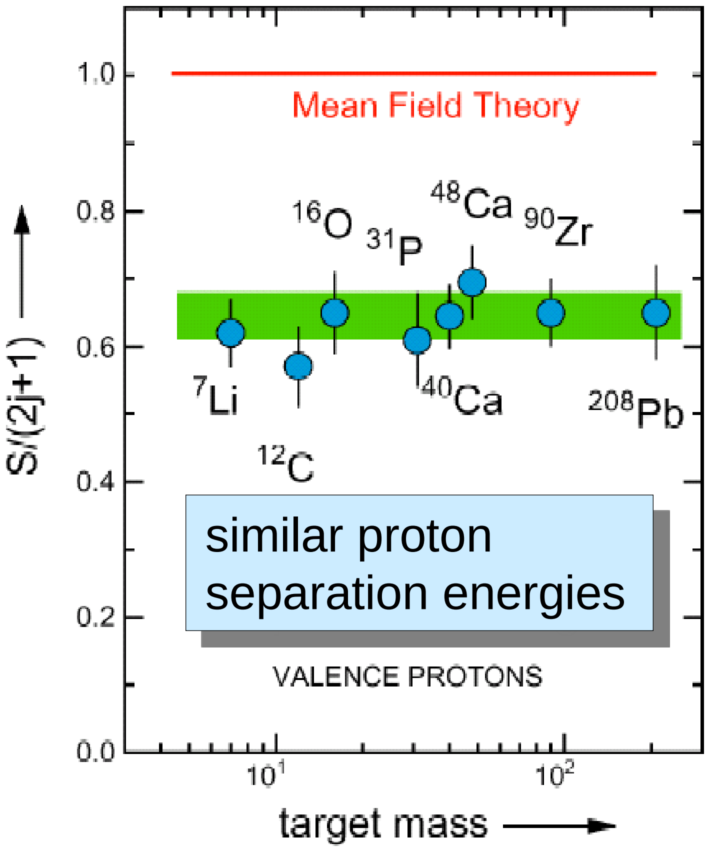
Electron induced proton knockout reactions: [A,Z] (e,e′p) [A-1,Z-1]

Reduction in spectroscopic strength relative to mean-field prediction

Only 60-70% of the protons participate in independent-particle motion in valence states



Systematics of (e,e′p) on Stable Nuclei at NIKHEF

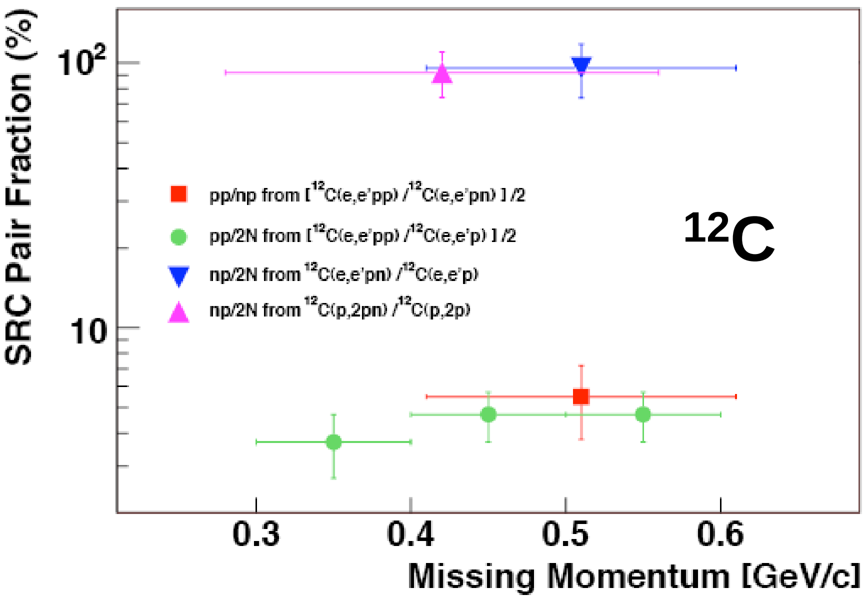


W. Dickhoff & C. Barbieri, Prog. Nucl. Part. Sci., 52 (2004) 377.

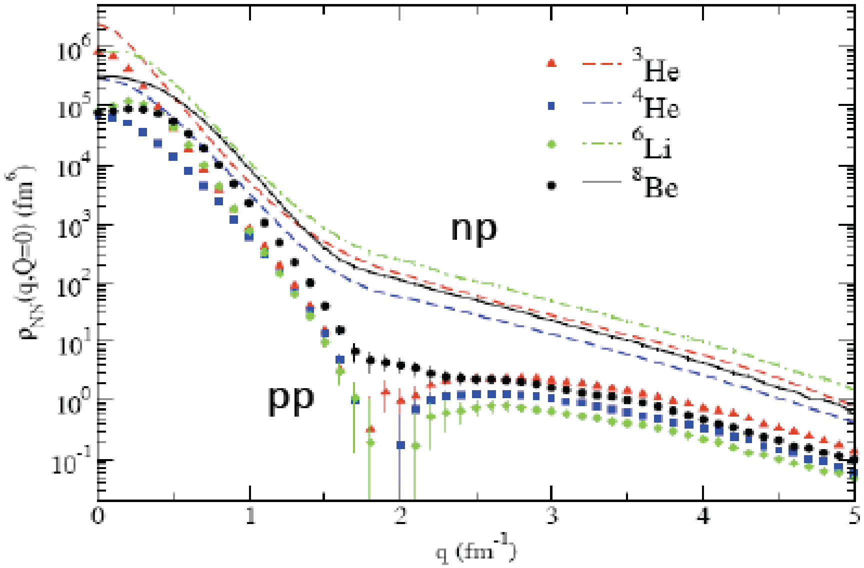
Low occupancy caused by correlated pairs of nucleons within the nucleus, i.e. effect of long-range, tensor and short-range correlations

Short-Range and Tensor Correlations in Symmetric Nuclei

From high-momentum transfer nucleon knockout reactions (e,e'p), (e,e'pN) and (p,2pN) and (e,e') data on stable nuclei
(JLab, BNL, NIKHEF, Mainz …)



R. Subedi et al., Science 320 (2008) 1476.



R. Schiavilla et al., PRL 98 (2007) 132501.

np pairs dominate SRC – 20 times more likely than pp pairs

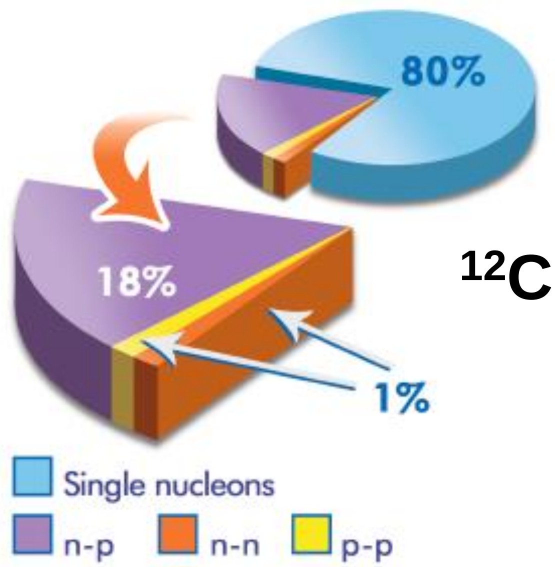
- ❖ **Direct consequence of NN tensor force**
- ❖ **Implications for description of n stars?**

2N momentum distributions calculated for g.s. of light nuclei using realistic Hamiltonian with 2- and 3-body potentials (AV18/UIX)

- ❖ Much larger for np pairs than pp pairs for relative momentum ~ 300-600 MeV/c
- ❖ Universal character originating from tensor components in realistic NN potential

Short-Range and Tensor Correlations in Symmetric Nuclei

R. Subedi et al., Science 320 (2008) 1476.



^{12}C

- ❖ **80 ± 5% single particles moving in average potential**

  60-70% independent single particle in a shell-model potential

  10-20% shell model long-range interactions

- ❖ **20 ± 5% two-nucleon short-range and tensor correlations**

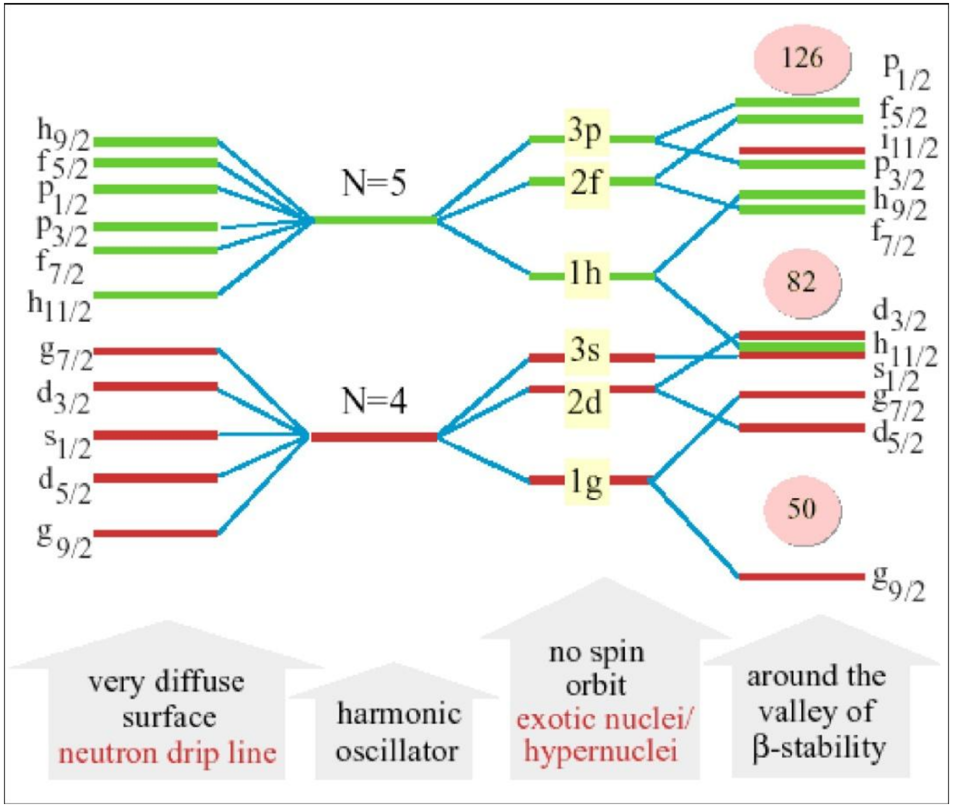
R. Schiavilla et al., PRL 98 (2007) 132501.

Correlations induced by tensor force strongly influence the structure of np pairs, which are predominantly in deuteron-like states (T=0, S=1), while ineffective for pp pairs, which are mostly in T=1, S=0 quasi-bound states.

New experiments to explore 2N and 3N SRCs planned at Jlab:
(e,e') in $^{3}He/^{3}H$ and $^{48}Ca/^{40}Ca$
(e,e'pN) on ^{4}He
Isospin dependence?

Isospin Dependence of Mean Field and Residual Interactions

How do short-range, tensor and long-range NN correlations evolve in nuclei and nuclear matter as a function of isospin and density?



Shell structure predicted to change in exotic nuclei (particularly in neutron rich nuclei)

Weak binding, impact of the particle continuum, collective skin modes and clustering in the skin…

Mean-field modifications

- surface composed of diffuse neutron matter
- derivative of mean field potential weaker and spin-orbit interaction reduced

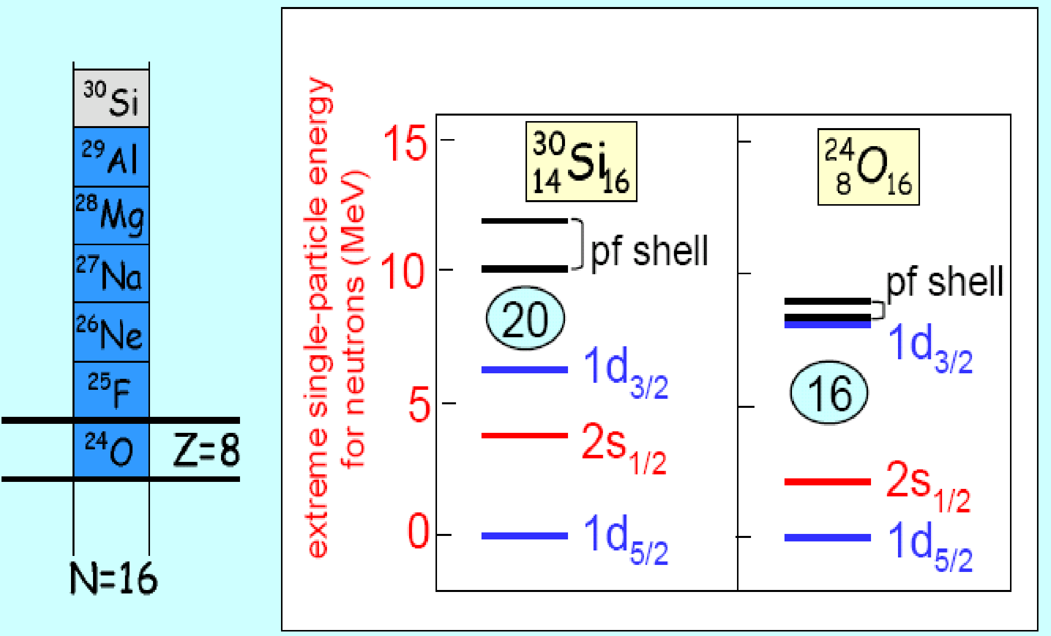
Residual interaction modifications

- partly occupied orbits
- $V_{\sigma\tau}$ monopole interaction: coupling of proton-neutron spin-orbit partners
- deformed intruder configurations

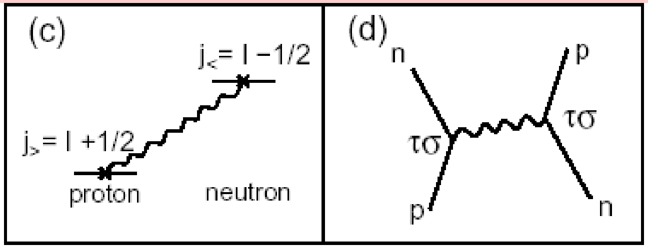
New Magic Number at N=16

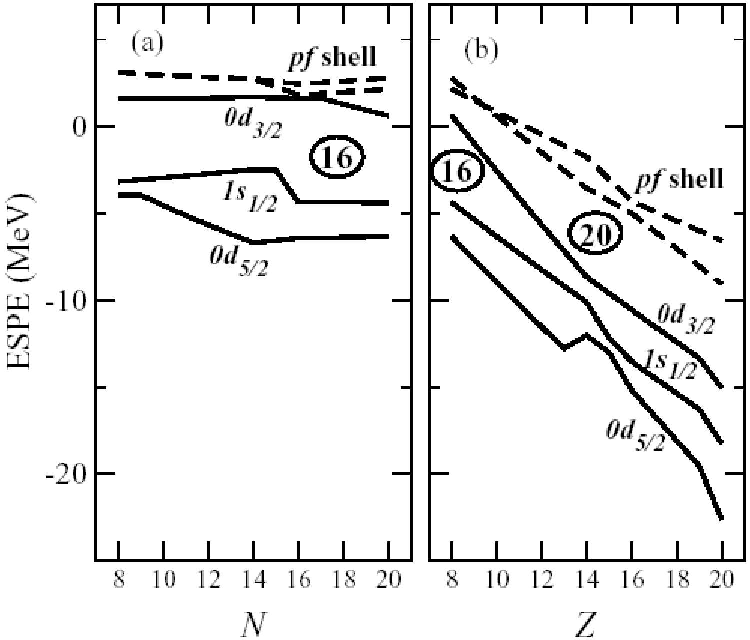
$V_{\sigma\tau}$ monopole interaction : coupling of proton-neutron spin-orbit partners

Present in stable nuclei but missing in n-rich nuclei where the spin-orbit partner state of the valence neutrons are not occupied by protons



T. Otsuka *et al*. Phys. Rev. Lett. 87 (2001) 082502.



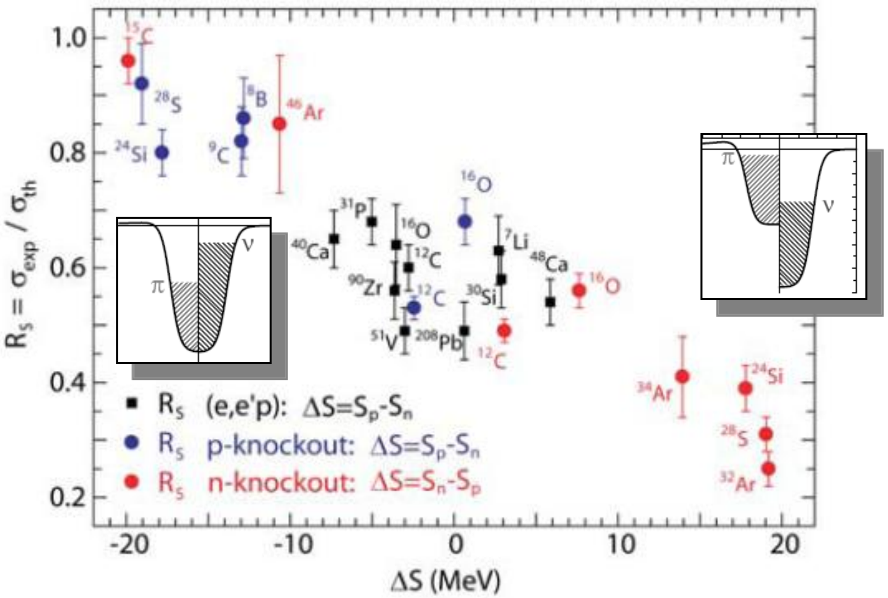


Examples of experimental evidence:

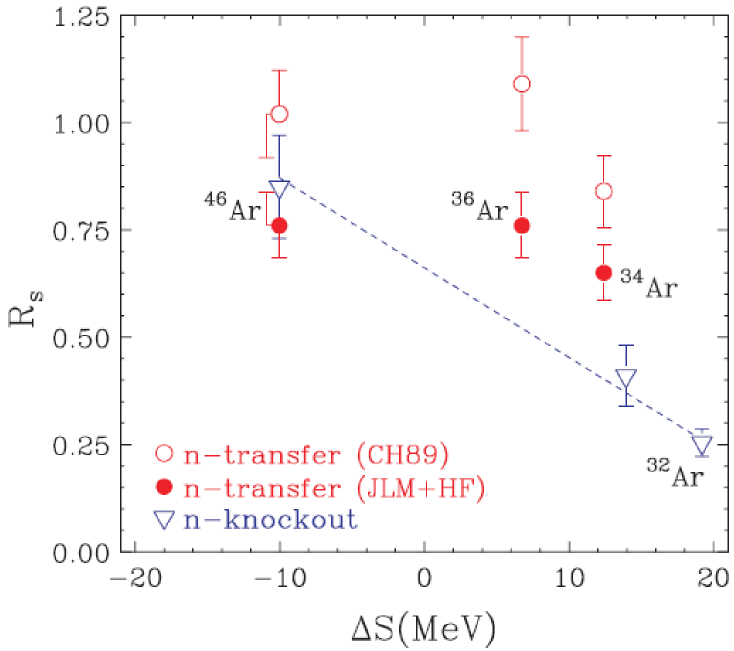
- Two-neutron separation energies
- In-beam fragmentation gamma spectroscopy
- Interaction cross-sections and longitudinal momentum distributions (direct reactions)

Correlations in Asymmetric Nuclei

Are NN correlations modified in isospin-asymmetric nuclei and nuclear matter?



A. Gade et al., Phys. Rev. C 77 (2008) 044306.



J. Lee et al., PRL 104 (2010) 112701.

Spectroscopic factors for valence nucleons in asymmetric nuclei extracted from nucleon-removal reactions on light nuclear targets and transfer reactions performed **with radioactive ion beams.**

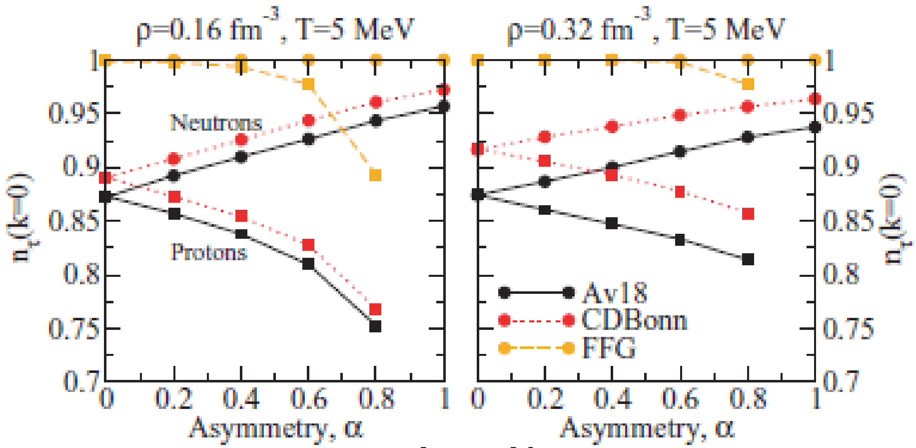
Strong dependence on isospin asymmetry:

- R_S close to 1 for loosely-bound valence n in n-rich nuclei (expected in low-density nuclear matter)
- Suppression of single-particle strength for strongly-bound n in n-poor nuclei

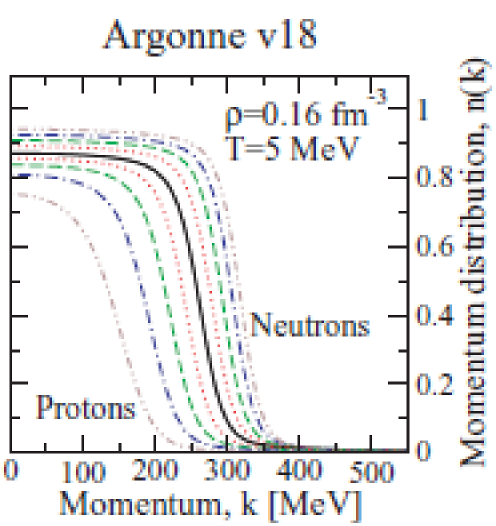
Not yet understood

Correlations in Asymmetric Nuclei

Isospin dependence of SRC in infinite nuclear matter studied using SCGF method and realistic NN interactions



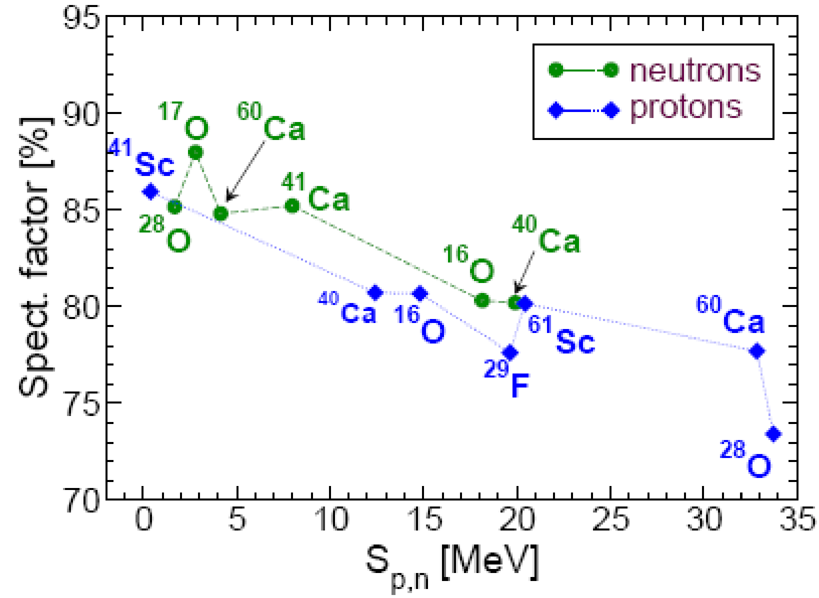
$\alpha = (\rho_n - \rho_p)/\rho$



A. Rios et al. PRC 79 (2009) 064308.

Ab-initio calculations:

Self-Consistent Green's Function (SCGF) method using realistic chiral N3LO force + G-matrix for effects of SRC



C. Barbieri et al., arXiv:0909.0336v2 (2009).

❖ Significant change of depletion in momentum distributions with isospin asymmetry

❖ Asymmetry dependence of spectroscopic factors similar (but smaller) than observed experimentally – on-going theoretical effort, effect may increase with improved interactions

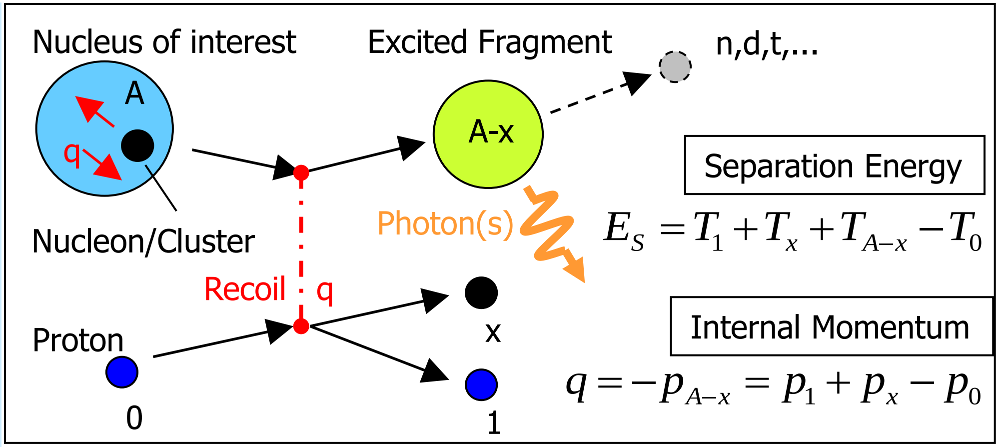
Experimental Probes

❖ **Proton and electron induced quasifree scattering (QFS) e.g. (e,e'p), (p,2p), (p,pn)...**

Most direct experimental probes to investigate single-particle properties of nuclei and the role of nucleon-nucleon correlations

❖ **Construct spectral functions for bound nucleons**
(probability that a nucleon as a certain energy and momentum within the nucleus)

Integrated strength => spectroscopic factors, occupation probabilities



To probe SRC (short distance scales)
=> high energy and momentum
=> **Need high energy beams**

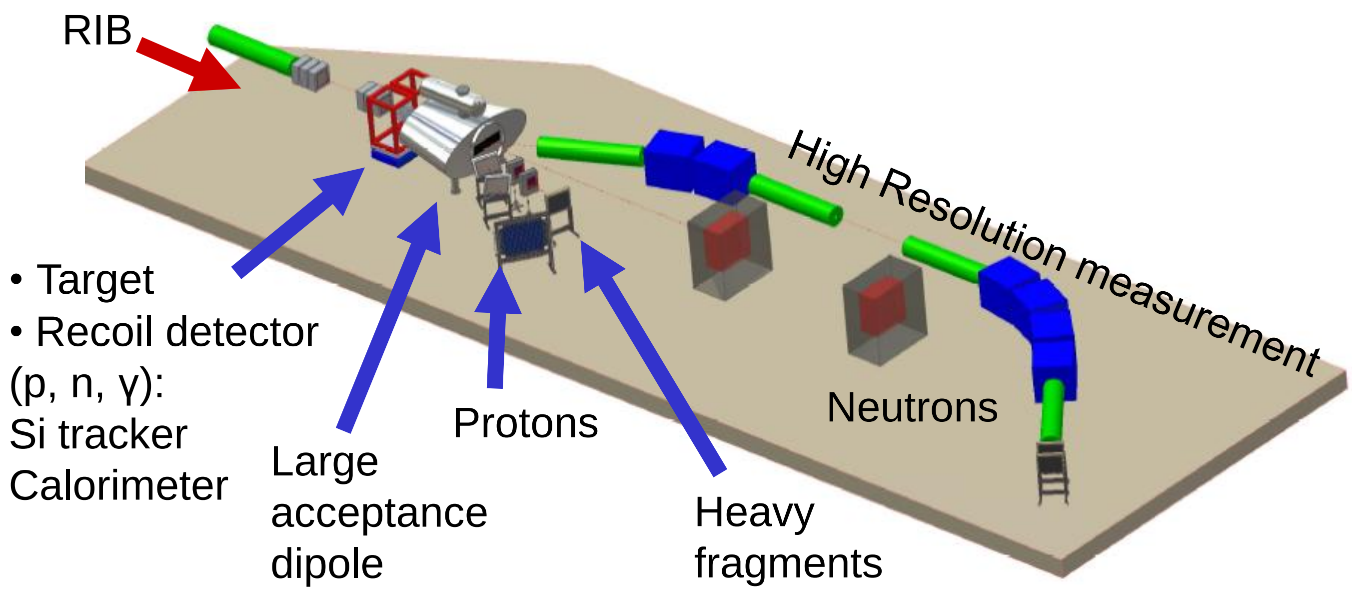
Both valence and deeply-bound nucleons can be removed
⇒ different densities probed
⇒ disentangle LRC and SRC

High-energy, high-intensity radioactive ion beams at GSI (and in future at FAIR)
➡ **opportunity to perform such studies with isospin asymmetric nuclei**

The R^3B Experiment at FAIR

Universal setup for kinematical complete measurements of high-energy reactions

R^3B
Reactions with
Relativistic
Radioactive
Beams

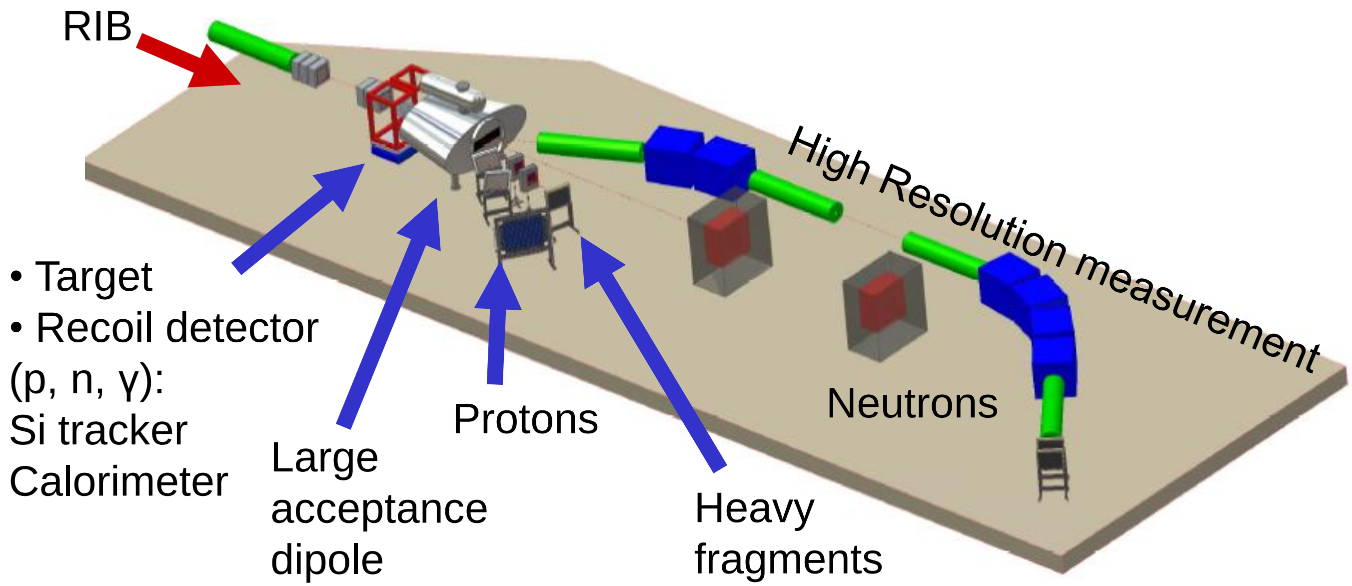


Experiments	**Physics goals**
➢ elastic scattering	radii, matter distribution
➢ knockout and quasi-free scattering	single-particle occupancies, spectral functions, correlations, clusters, resonances beyond the drip lines
➢ electromagnetic excitation	single-particle occupancies, astrophysical reactions (S factor), soft coherent modes, giant resonance strength, B(E2)
➢ charge-exchange reactions	Gamov-Teller strength, spin-dipole resonance, neutron skins
➢ fission	shell structure, dynamical properties
➢ spallation	reaction mechanism, applications (waste transmutation, ...)
➢ fragmentation	γ-ray spectroscopy, isospin-dependence in multifragmentation

The R^3B Experiment at FAIR

Universal setup for kinematical complete measurements of high-energy reactions

R^3B
Reactions with
Relativistic
Radioactive
Beams

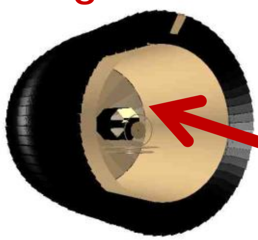


- identification and beam "cooling" (tracking and momentum measurement, $\Delta p/p \sim 10^{-4}$)
- exclusive measurement of the final state:
  - identification and momentum analysis of fragments
    (large acceptance mode: $\Delta p/p \sim 10^{-3}$, high-resolution mode: $\Delta p/p \sim 10^{-4}$)
  - coincident measurement of neutrons, protons, gamma-rays, light recoil particles
- **applicable to a wide class of reactions**

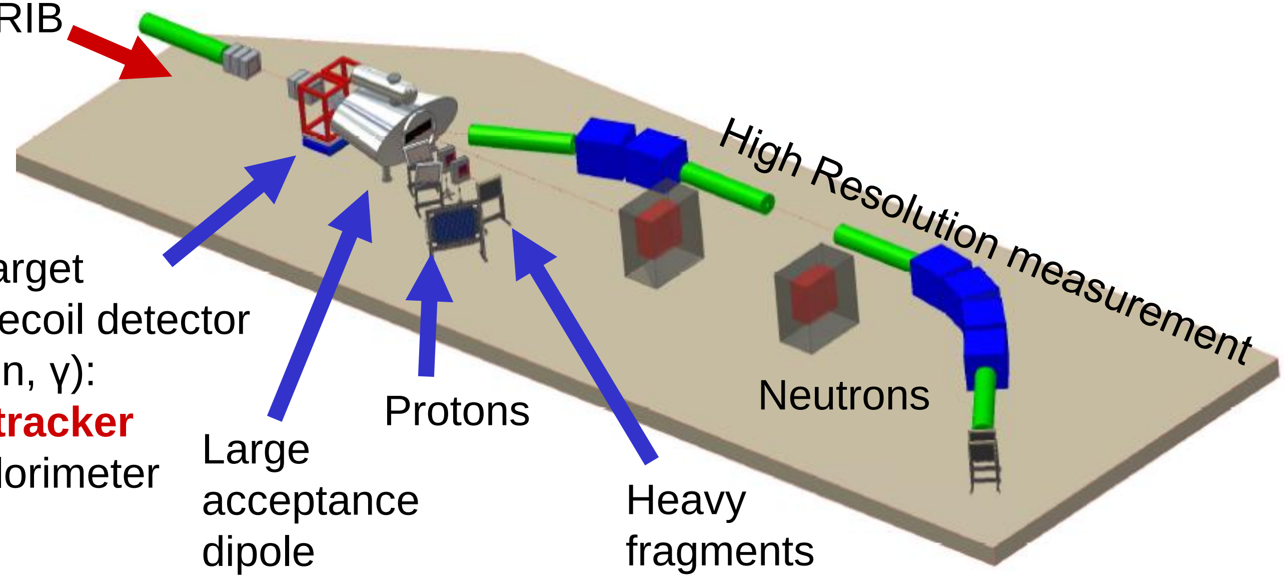
The R^3B Experiment at FAIR

Universal setup for kinematical complete measurements of high-energy reactions

NUSTAR grant



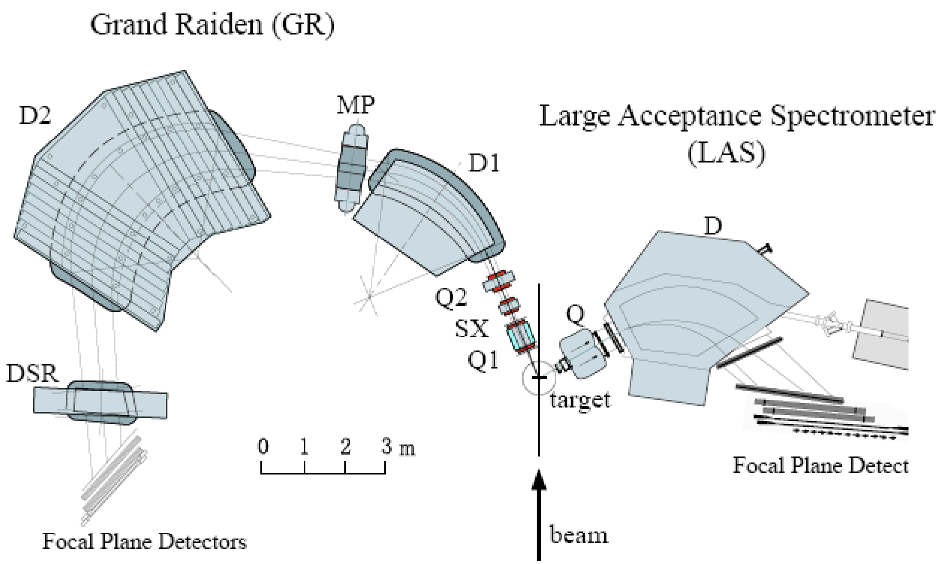
• Target
• Recoil detector (p, n, γ):
Si tracker
Calorimeter



Proton-induced low- and high-momentum transfer quasifree scattering reactions, e.g. (p,2p) and (p,pn), in inverse kinematics using relativistic radioactive ion beams at GSI/FAIR (0.5-2 AGeV)

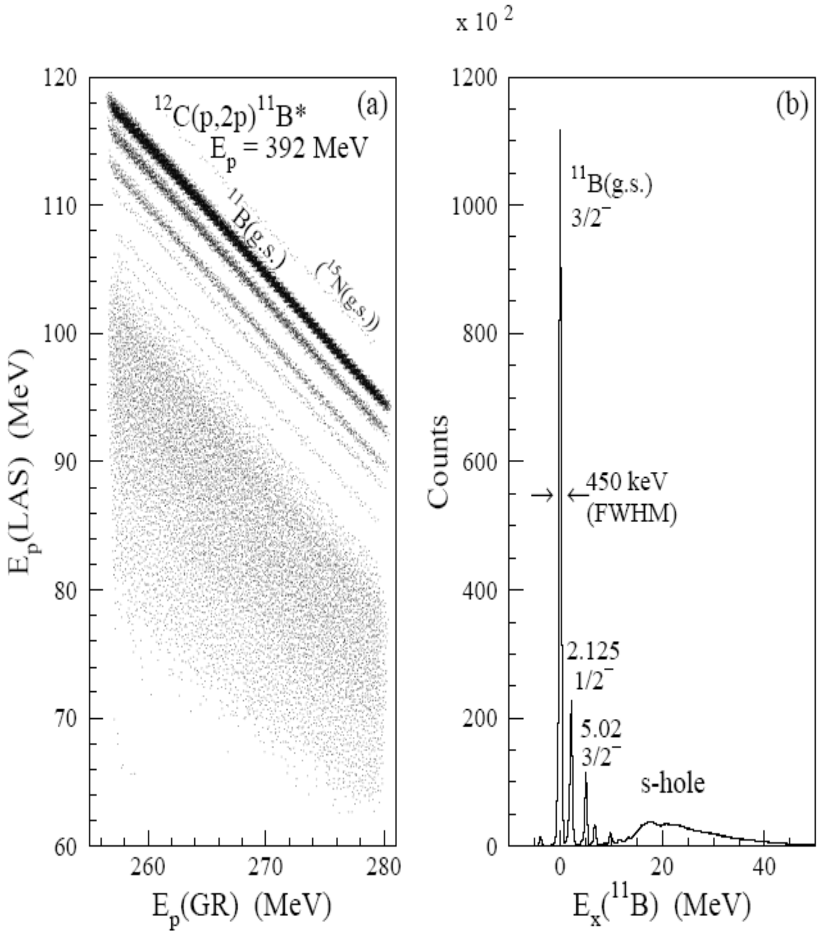
• Measurements of spectral functions of **both valence and deeply-bound nucleons** in isospin asymmetric nuclei
• Comparison to **modern many-body theories** of nuclei and nuclear matter using realistic nucleon-nucleon interactions
• Future measurements of **polarization observables** foreseen.

Recent QFS Experiment in Normal Kinematics: $^{12}C(p,2p)^{11}B$



Study of deep-hole states ($s_{1/2}$)

M. Yosoi et al., Phys. Lett. B 551, 255 (2003).
M. Yosoi, PhD Thesis, 2003, Kyoto University

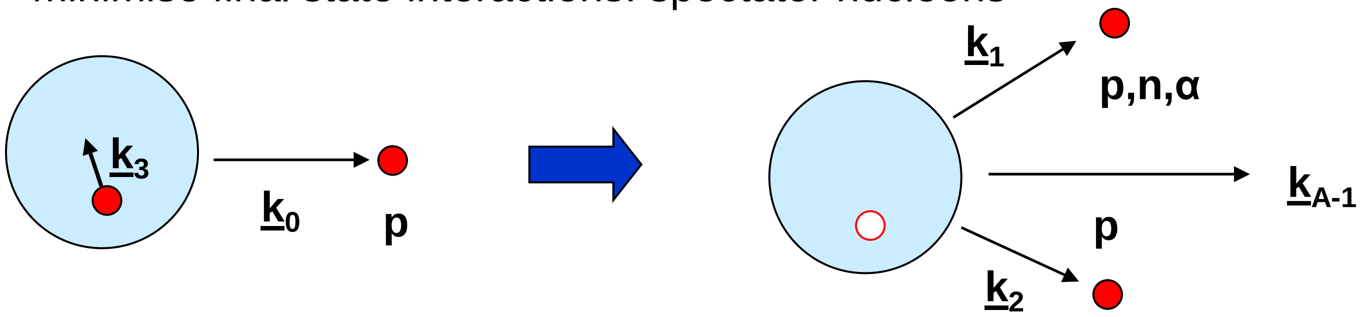


RCNP, Osaka
E_p = 392 MeV
Two spectrometer measurement
Energy resolution (FWHM) ≈ 450 keV

Quasifree Scattering in Inverse Kinematics

High energy heavy ion beams, E = 100-1000 A.MeV

- simplify reaction mechanism: impulse approximation
- minimise final state interactions: spectator nucleons



Could measure **momentum distribution k_{A-1}** in two ways:
- **directly**
- **indirectly** by measuring k_1 and k_2 **as in normal kinematics**

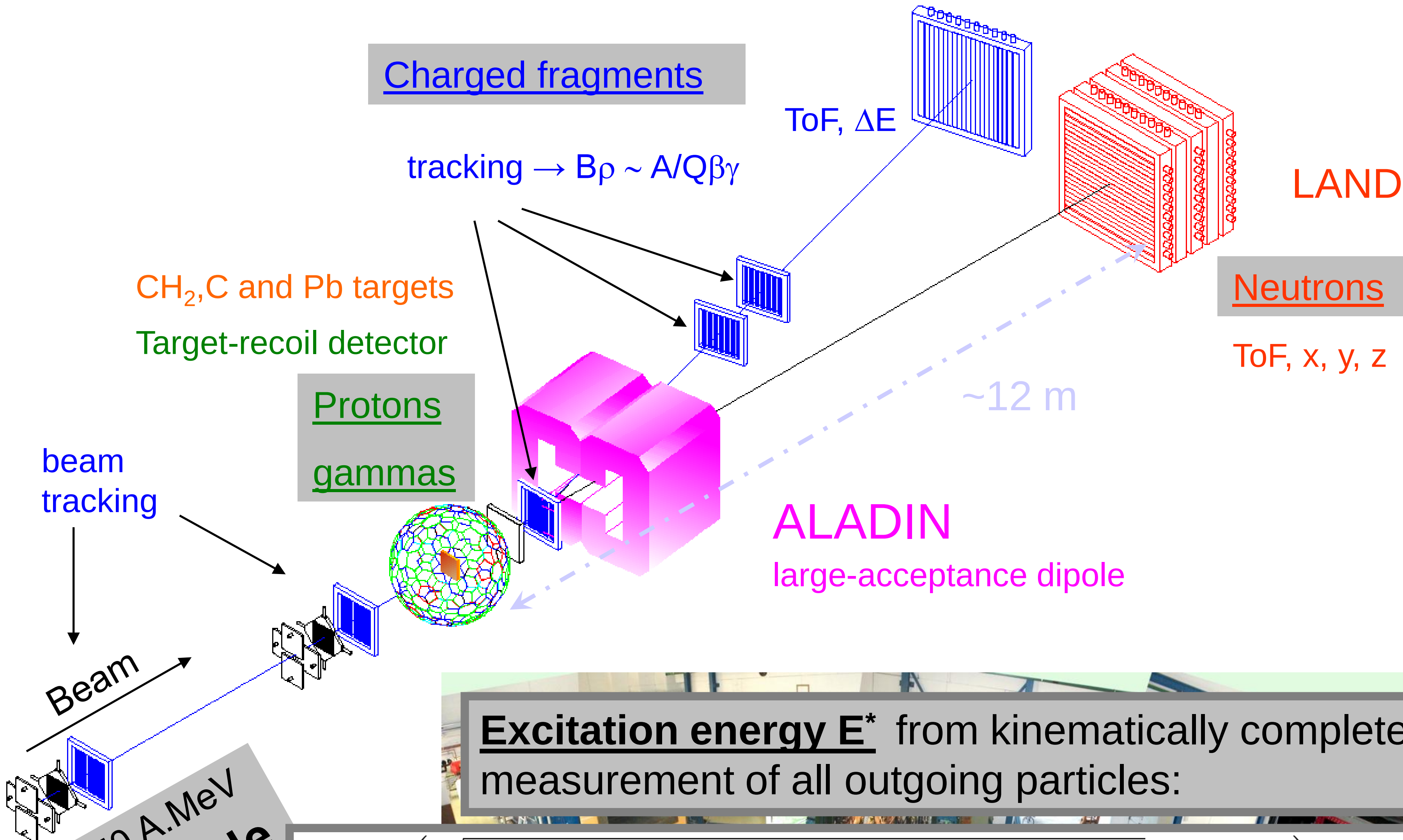
Better understanding of final state interactions

In inverse kinematics, k_{A-1} is related to momentum of struck nucleon k_3 by :

$$k_3 = \frac{A-1}{A} k_A - k_{A-1}$$

Hence, by only measuring k_{A-1} we can obtain:
- l-value from momentum distribution of core
- energy of core states can be obtained with γ-rays

The ALADIN/LAND Set-up at GSI

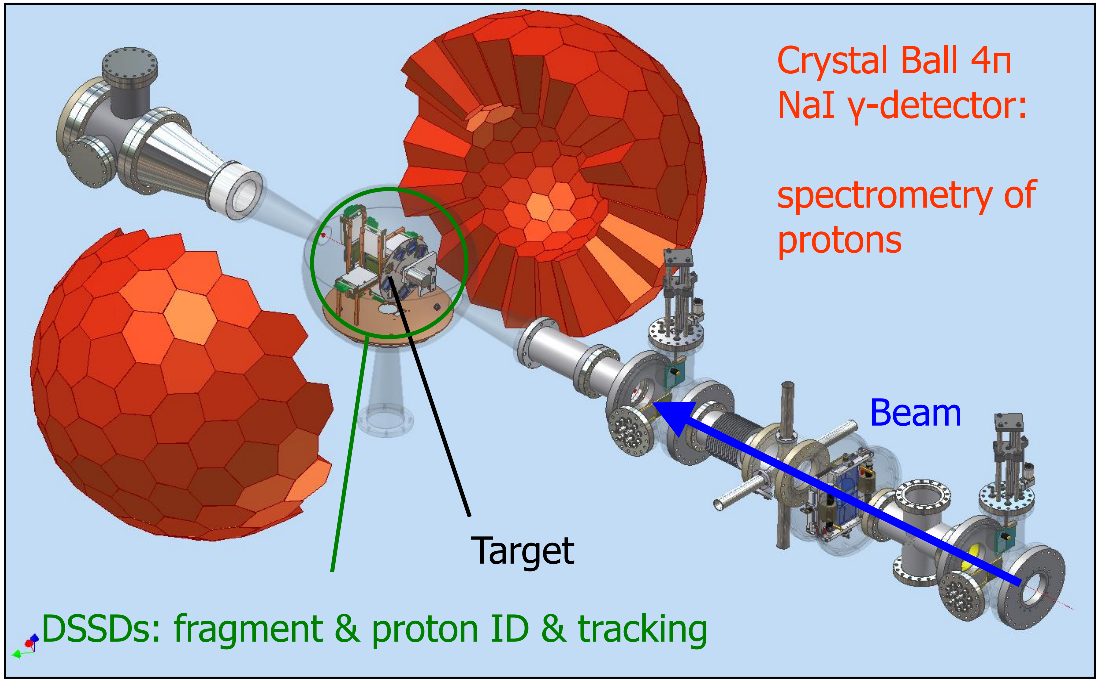


Excitation energy E* from kinematically complete measurement of all outgoing particles:

$$E^* = \left(\sqrt{\sum_i m_i^2 + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos\theta_{ij})} - m_{proj}\right) c^2 + E_\gamma$$

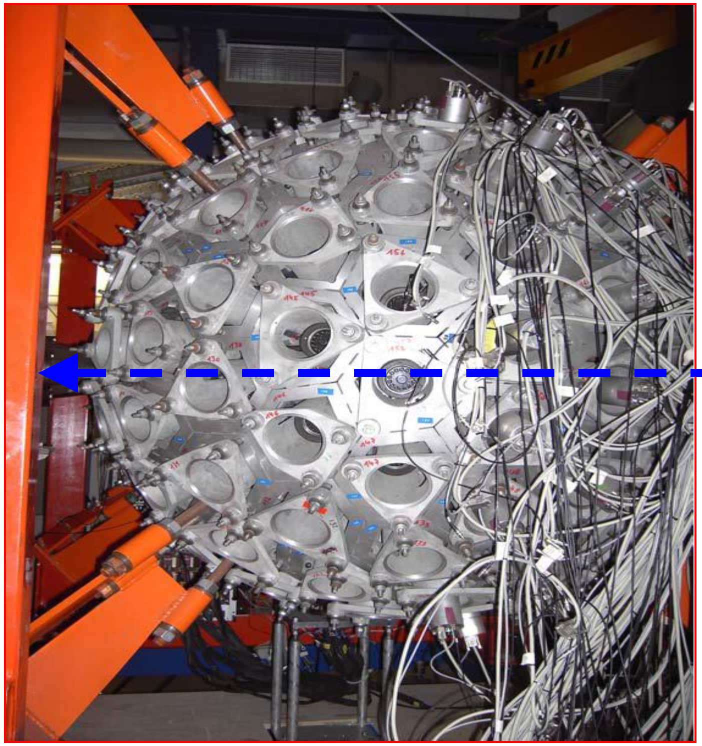
Target-Recoil Detector for QFS Experiments

Detectors around the reaction target:

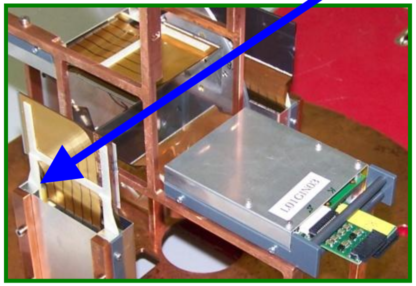


New: Crystal Ball for γ-rays and protons

- 4π gamma detector (~1980 - ...)
- 162 NaI(Tl) crystals of 20 cm length
- Measure energy of recoil protons with additional low-gain readout of the forward 64 crystals (~ 2π)

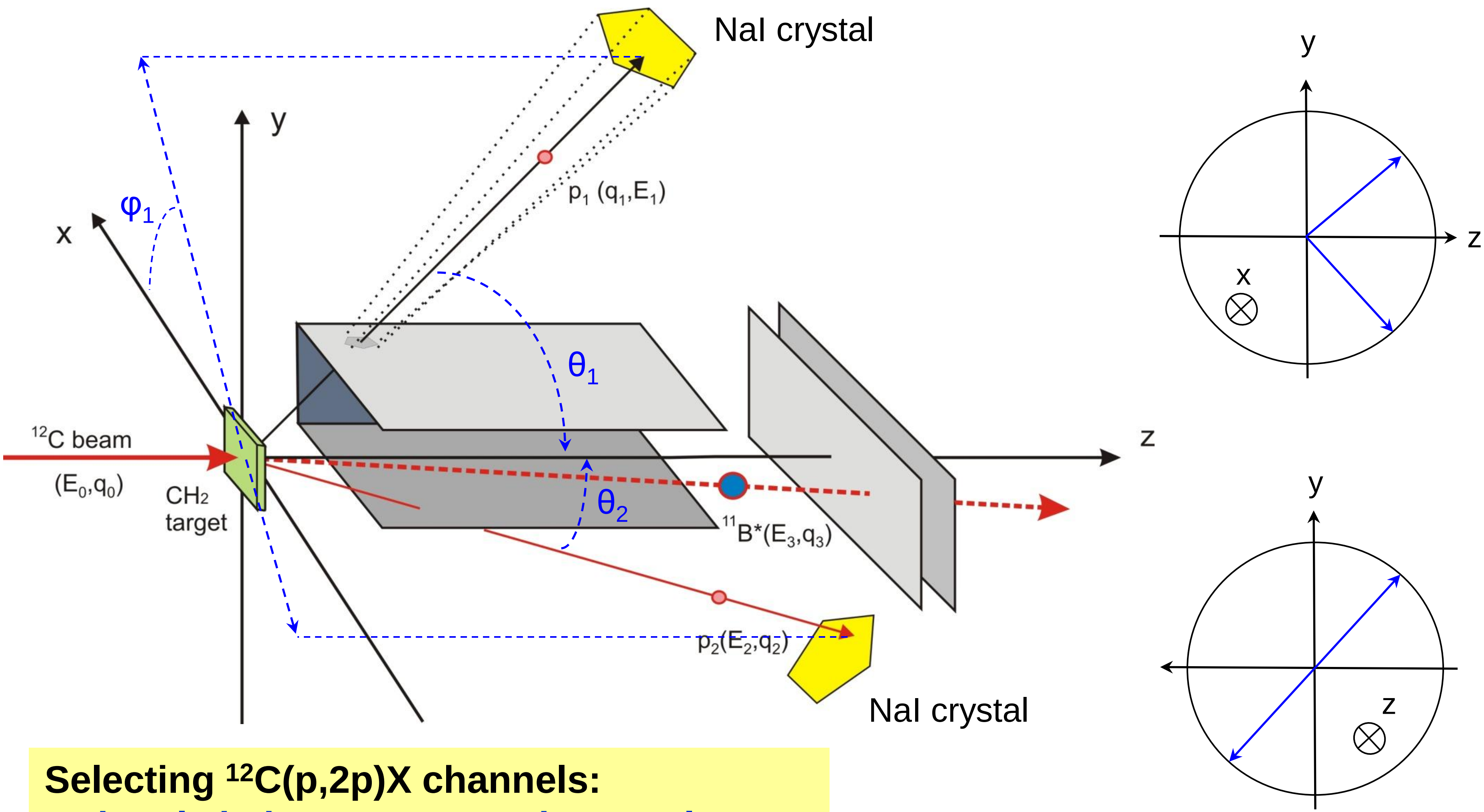


New: DSSDs for proton and fragment tracking



- 4 box detectors for proton tracking
- polar angle coverage ≈ 15°≤ θ ≤ 80°
- resolution: Δx ~ 100 μm; ΔE ~ 50 keV
- range: 100 keV < E < 14 MeV
- 2 in-beam detectors for tracking & ID of fragments and protons

Angular Correlations of Two Protons from (p,2p) Reaction

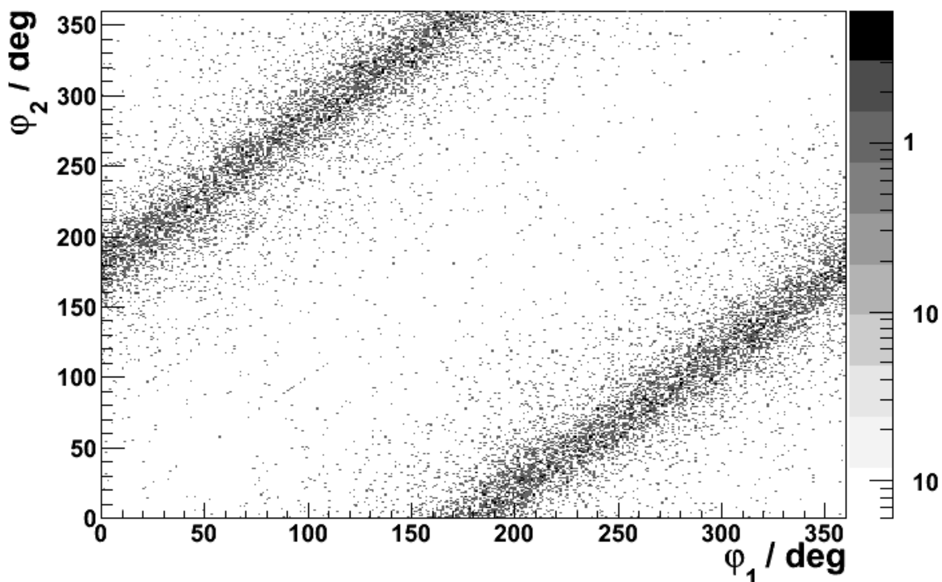


Selecting $^{12}C(p,2p)X$ channels:
2 signals in box DSSDs and 2 NaI clusters with similar angle in Crystal Ball

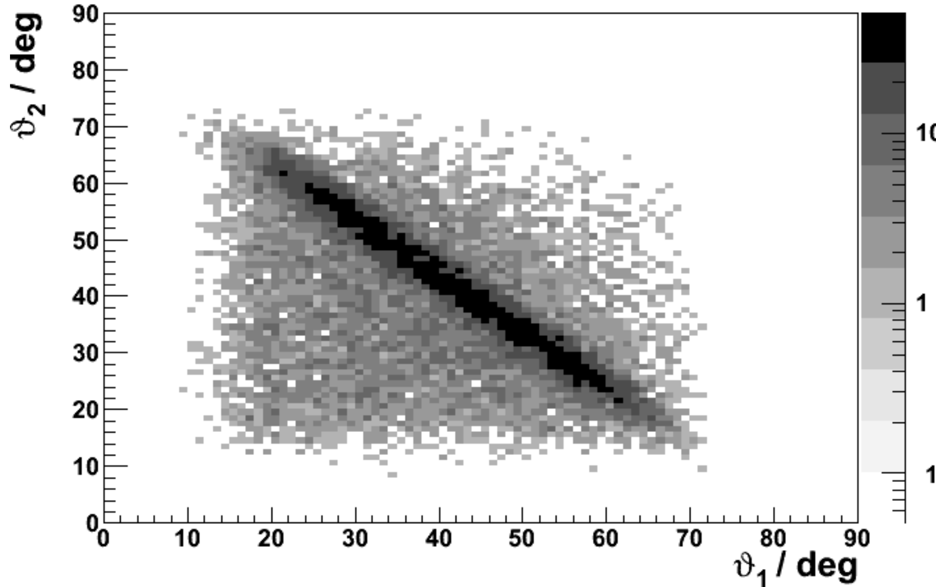
Angular Correlations of Two Protons from ^{17}Ne(p,2p) Reaction

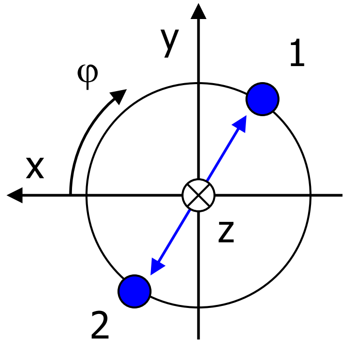
Selection of QFS (p,2p) events: Very clear characteristic angular correlations

φ_1 vs φ_2 distribution



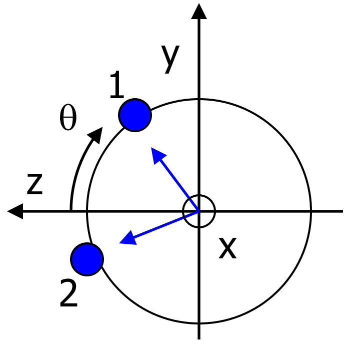
θ_1 vs θ_2 distribution





Looking along beam:

Correlation in φ:
$\Delta\varphi = 180°$



Looking from side:

Anti-correl. in θ:
Opening angle ≈ 80°

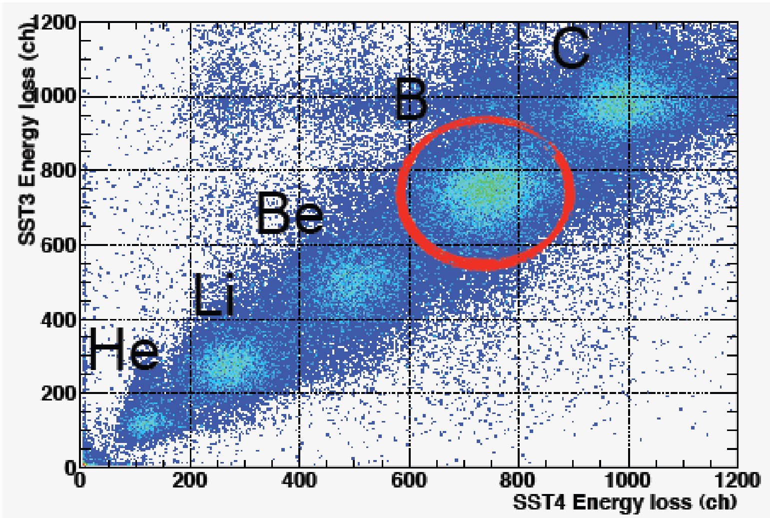
F. Wamers, GSI

^{12}C(p,2p)^{11}B in Inverse Kinematics

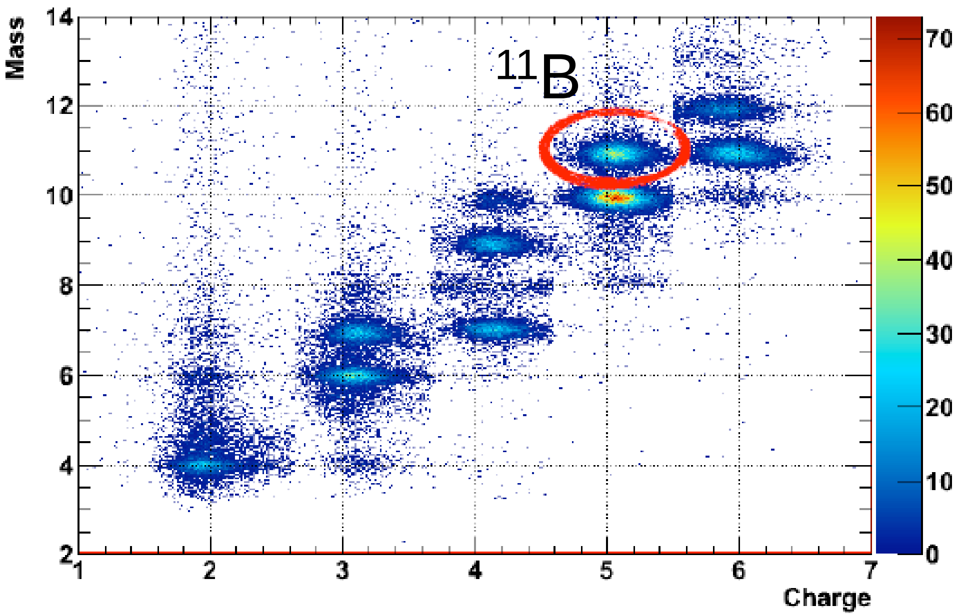
PhD Thesis J. Taylor, Liverpool (see poster)

- Benchmark the QFS experimental technique in inverse kinematics for future experiments with RIBs at GSI/FAIR
- Provide useful information for the design of the new R3B target-recoil detector

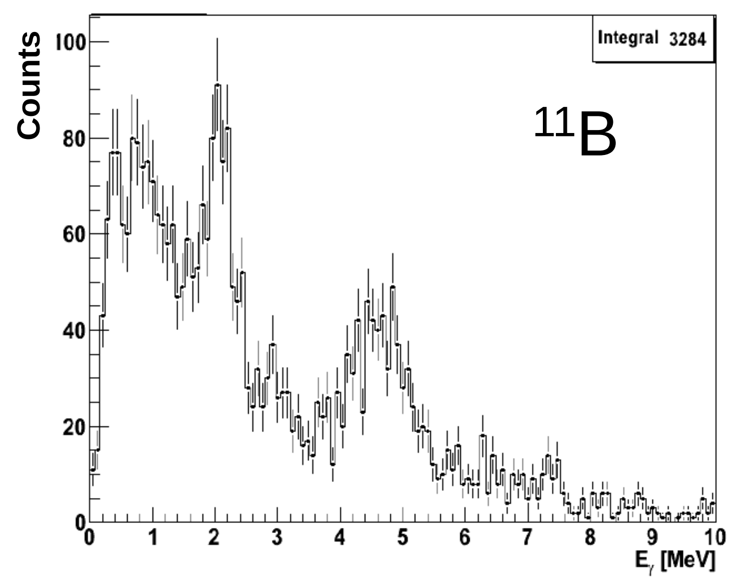
PID in Target-Recoil Detector DSSDs



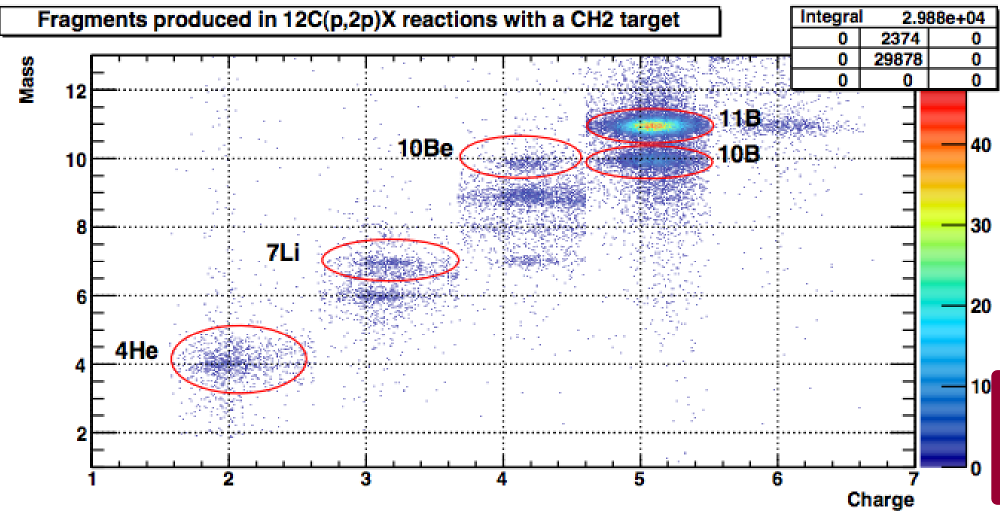
PID of outgoing fragments



γ-ray energy spectrum in Crystall Ball



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



PhD Thesis J. Taylor, Liverpool (see poster)

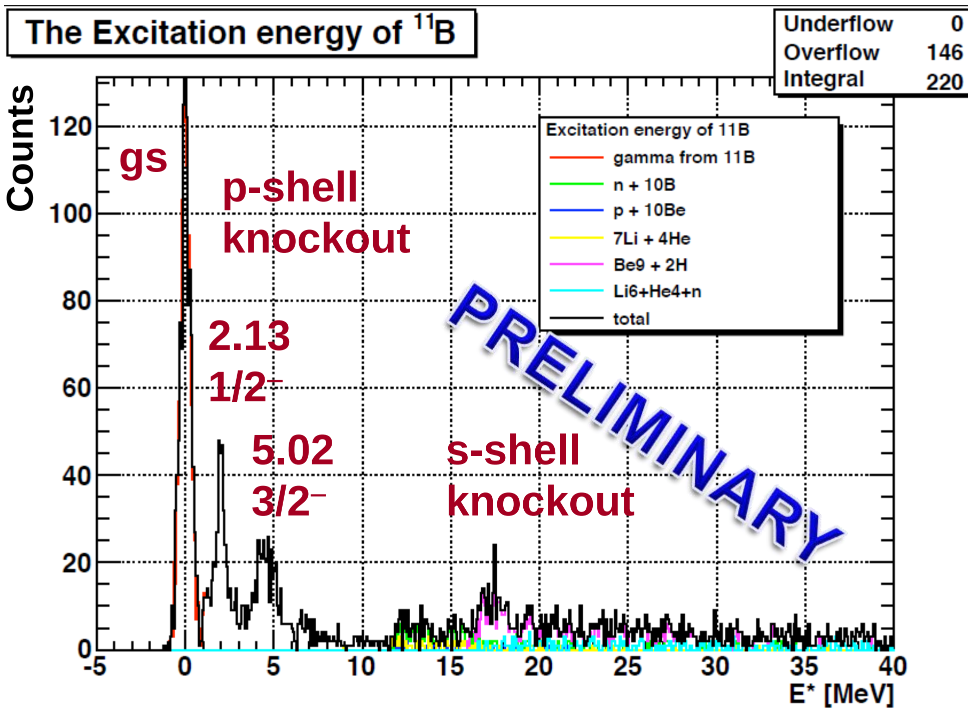
Excitation energy spectrum for ^{11}B reconstructed by invariant mass method

$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j cos\vartheta_{ij})} + E_\gamma - m_{proj}$$

Decays from bound states:
γ-rays detected in the Crystal Ball

2- and 3-body $^{12}C(p,2p)X$ channels included in the reconstruction of the s-state:

$^{12}C(p,2p)^{10}B+n$	$^{12}C(p,2p)^{10}Be+p$
$^{12}C(p,2p)^{9}Be+d$	$^{12}C(p,2p)^{7}Li+\alpha$
$^{12}C(p,2p)^{6}Li+\alpha+n$	$^{12}C(p,2p)\alpha+\alpha+t$



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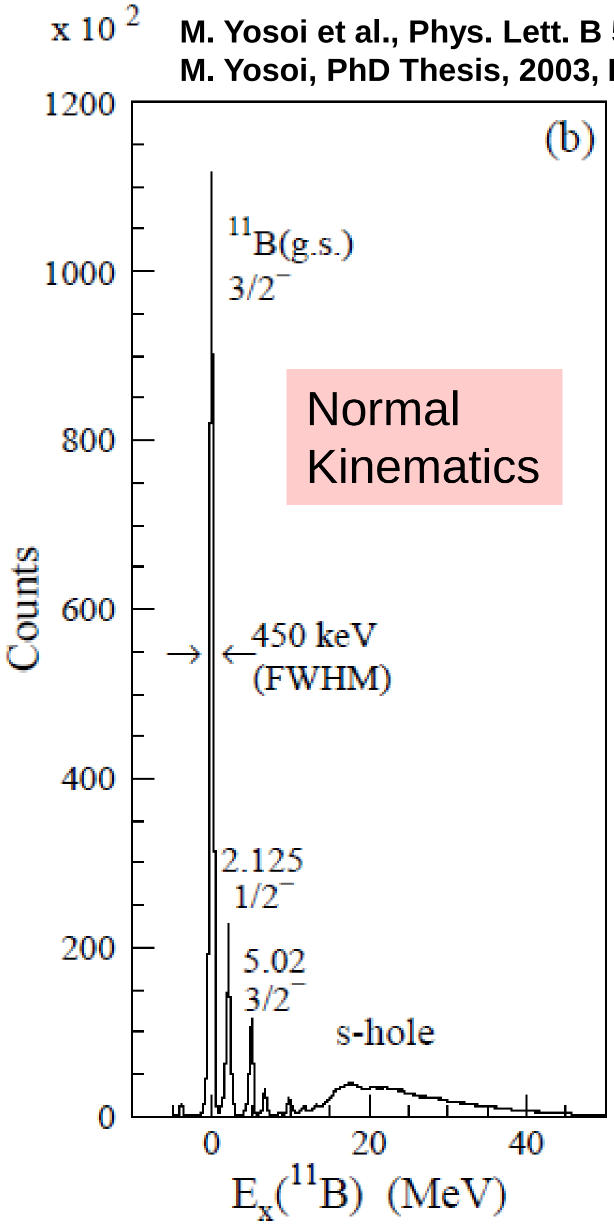

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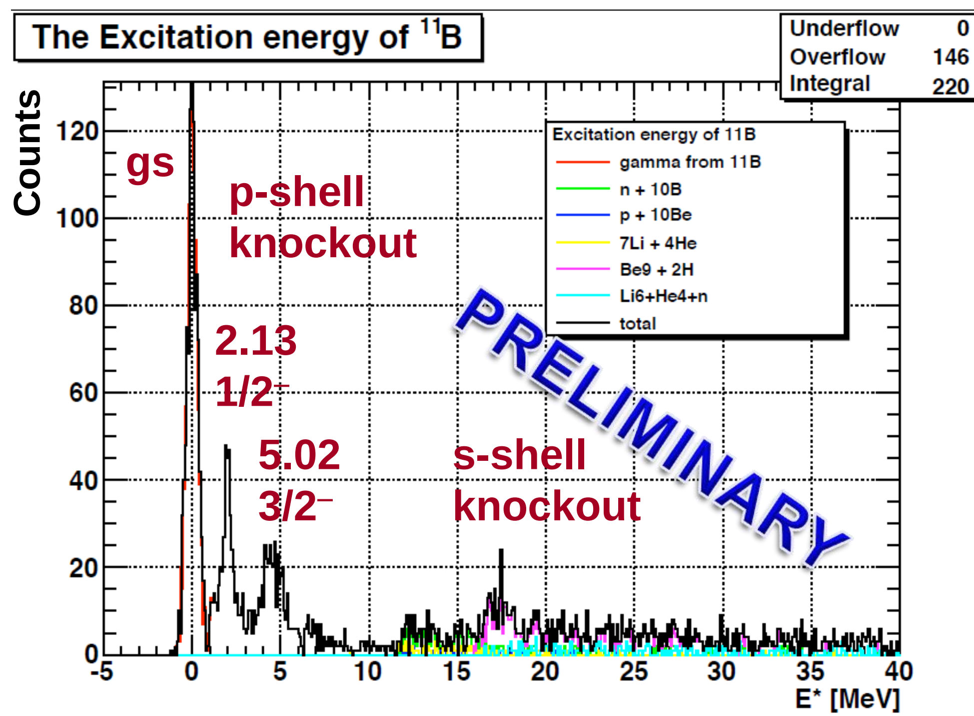
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i\neq j} \gamma_i\gamma_j m_i m_j (1-\beta_i\beta_j cos\vartheta_{ij})} + E_\gamma - m_{proj}$$



The near future

On-going research programme at GSI, before FAIR

Very rich research programme planned with the **high energy RIBs of the Super-FRS at FAIR**, e.g. R^{3}B, ASYEOS collaborations...
But we're also doing experiments today (e.g. with light neutron/proton-rich nuclei or stable beams)

R^{3}B

Neutron-Rich Nuclei at and Beyond the Dripline in the Range Z=4 to Z=10 Studied in Kinematically Complete Measurements of Direct Reactions at Relativistic Energies

Aims of experiment:
Five physics topics using RIBs

- ❖ r-process nucleosynthesis
- ❖ spectroscopy of valence and deeply bound nucleons in exotic nuclei
- ❖ isospin dependence of nucleon-nucleon correlations
- ❖ alpha clustering in exotic nuclei
- ❖ spectroscopy of unbound nuclei

Experiment was successfully run 6 months ago

Run as single experiment by R^{3}B Collaboration:

- ❖ Same experimental setup for all topics
- ❖ Same settings of FRS for all topics
- ❖ Use different reactions (⇒ targets)
  - heavy-ion induced electromagnetic excitation: Pb target; C target for background
  - (p,2p), (p,pn) and (p,pα) quasifree scattering: H in CH_2 target; C target for background
  - one- and two-neutron removal: C in CH_2 target

Summary

❖ High-energy RIBs at GSI, and at FAIR in the future, provide a unique opportunity to investigate how nucleon-nucleon correlations (SRC, Tensor, LRC) evolve in isospin-asymmetric nuclei and nuclear matter

❖ Proton-induced quasifree scattering reactions performed in inverse kinematics with high-energy RIBs are being pioneered using the ALADIN/LAND setup at GSI

❖ Future prospects at FAIR with the new R^3B experiment

See also poster by Jonathan Taylor (Liverpool) and talk by Zoe Matthews (Liverpool)

Collaborators

- **GSI Darmstadt**

T. Aumann, K. Boretsky, M.Heil, R.Plag, R. Reifarth, H. Simon, F. Wamers, V. Panin, D. Rossi et al.

- **University of Birmingham**

N. Ashwood, M. Barr, M. Freer et al.

- **University of Edinburgh**

T. Davinson, P. Woods et al.

- **University of Liverpool**

M. Chartier, J. Taylor et al.

- **University of Surrey**

W. Catford et al.

- **STFC Daresbury Laboratory**

M. Labiche, R. Lemmon et al.

And the international R^{3}B Collaboration

http://www.gsi.de/forschung/kp/kr/R3B_e.html

Special thanks to PhD students Jonathan Taylor (Liverpool), Valeri Panin and Felix Wamers (GSI Darmstadt)

Direct Reactions as Spectroscopic Tools

Bound-state wavefunction: asymptotic → central

Reaction mechanism: complex → simple

One-nucleon transfer reactions

- probes valence nucleons
- properties of single-particle levels
- spectroscopic factors, occupancies
- E_{beam} = 5 - 30 MeV/nucleon

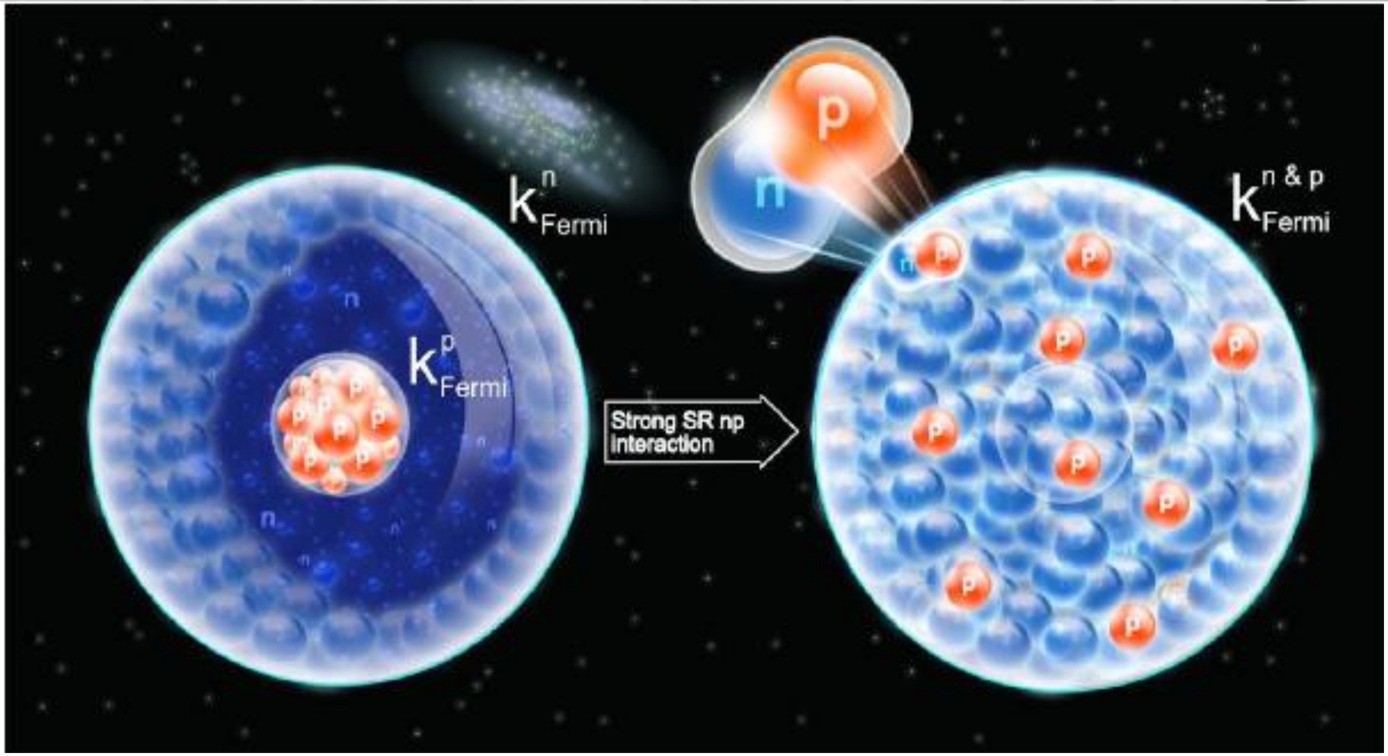
One-nucleon removal reactions

- probes valence nucleons
- properties of single-particle levels
- "absolute" spectroscopic factors, occupancies
- E_{beam} = 40 - 60 MeV/nucleon

Quasifree scattering reactions

- probes valence and deeply bound nucleons
- properties of single-particle levels
- "absolute" spectroscopic factors, occupancies
- in-medium n-n interaction
- E_{beam} = 200 - 1000 MeV/nucleon

Correlations in Neutron Stars



At the core of neutron stars, most accepted models assume :

- ~95% neutrons, ~5% protons and ~5% electrons (β-stability).
- Neglecting the np-SRC interactions, one can assume two separate Fermi gases (n and p).
- The proton contribution to the EOS is small: connection to Symmetry Energy

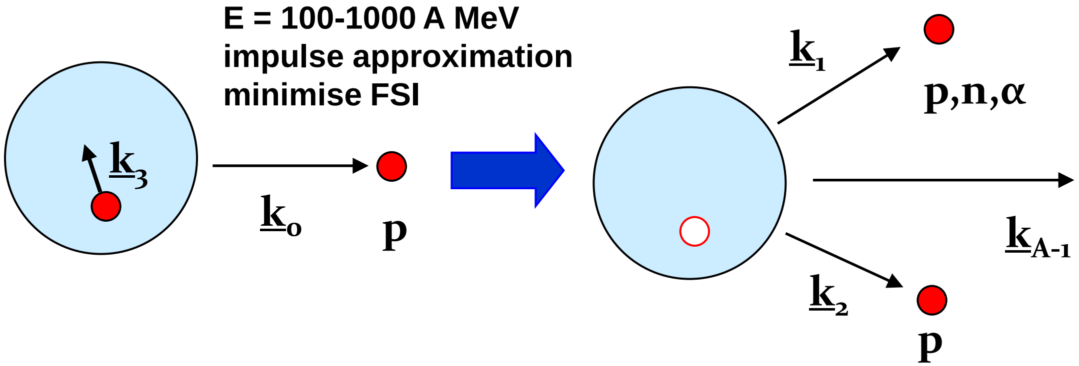
Since np interaction is x20 large than n-n interaction, possible implications are:

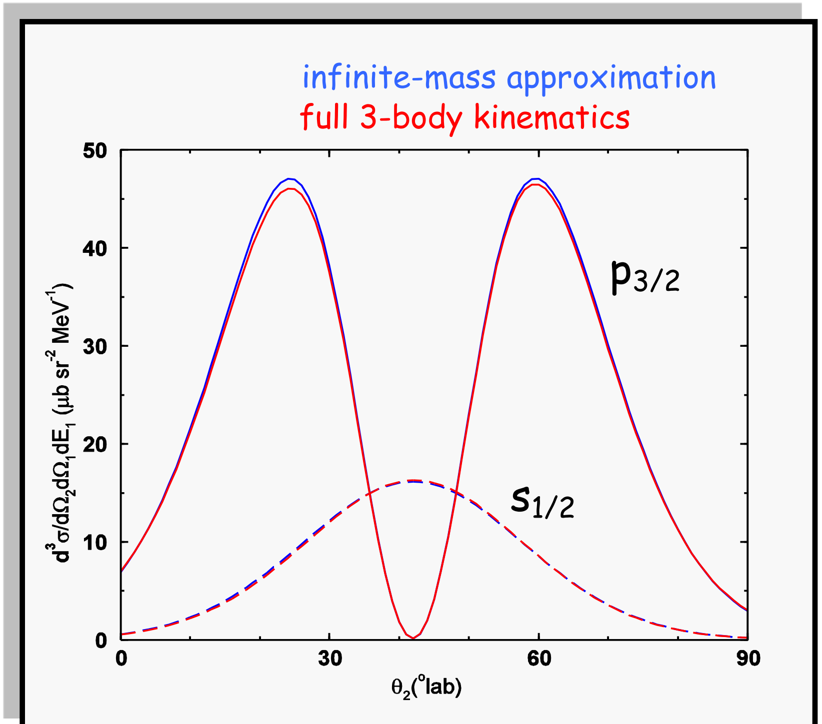
- The neutron gas heats the proton gas.
- Upper limit on the mass of neutron stars might be higher than predicted when neglecting the protons.
- Neutrino cooling rate might increase

Quasifree Scattering in Inverse Kinematics

Separation energies and momentum distributions of nucleons in nuclei

- ❖ Separation energy spectra give levels
- ❖ Angular correlation spectra give l-values





Valence *and* deeply-bound states

Distortion of the incoming and outgoing nucleon wavefunctions (from final state interactions, multiple scattering)

DWIA :

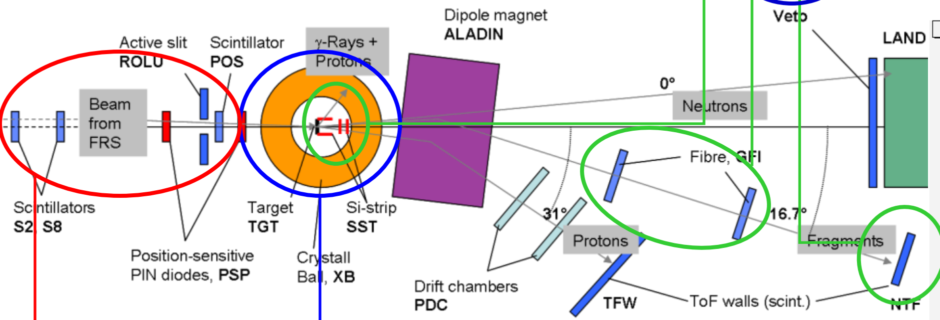
$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_2} = \underbrace{S_p}_{\text{spectroscopic factor}} F_k \underbrace{\frac{d\bar{\sigma}_{pp}}{d\Omega}\left(E_0, \theta, P_{eff}\right)}_{\text{free n-n cross-section}} \underbrace{G(\mathbf{k}_3)}_{\text{distorted proton momentum distribution}}$$

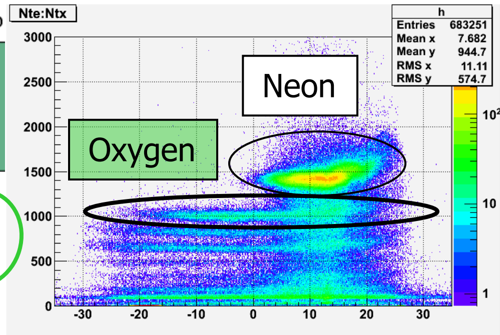
spectroscopic factor — free n-n cross-section — distorted proton momentum distribution

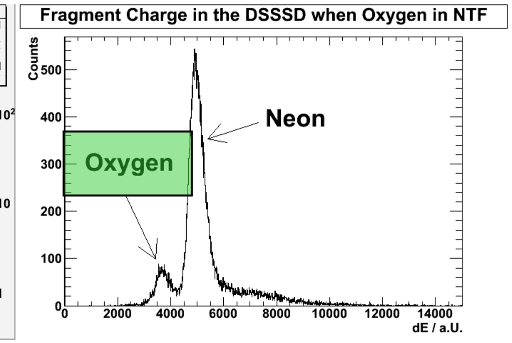
Selection of Reaction Channels: $^{17}Ne(p,2p)$

^{17}Ne ~ 500 AMeV: Pb / C / CH_2

ID & selection of reacted beam

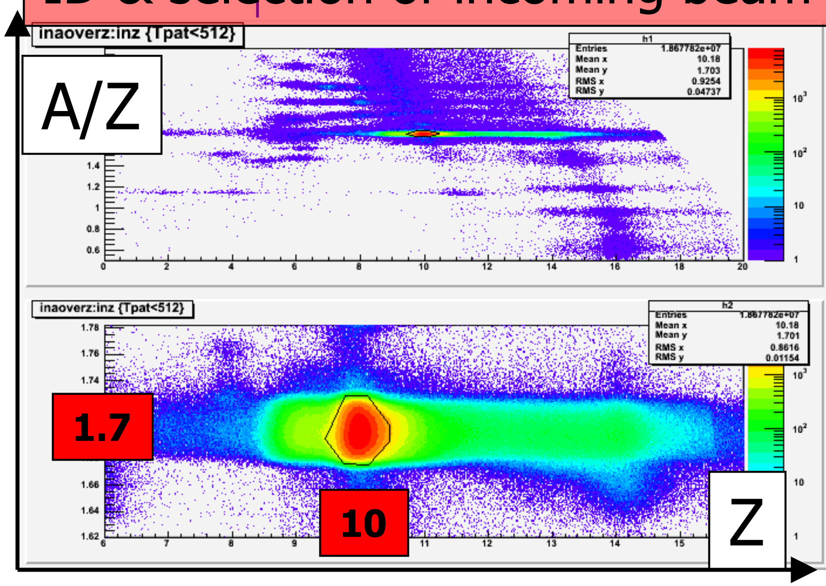


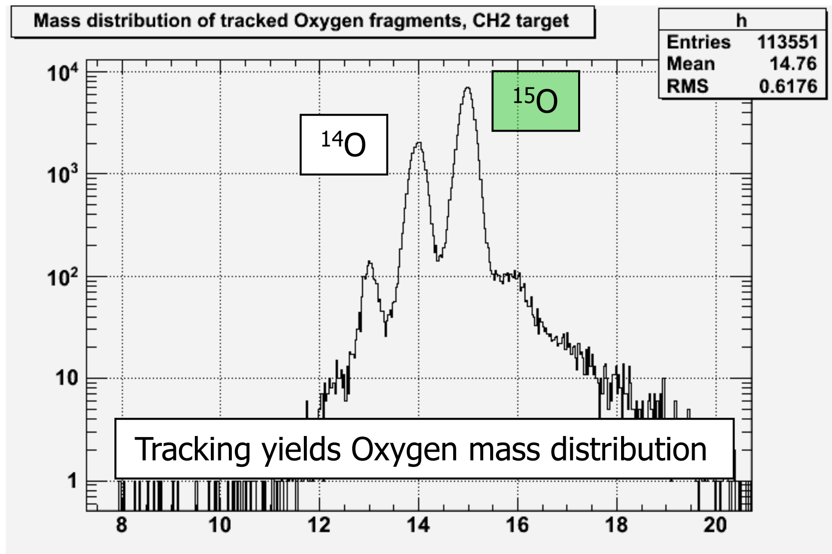




$^{17}Ne(p,2p)^{16}F \rightarrow {}^{15}O + X$

ID & selection of incoming beam





Select events with 2 charged particles in Crystal Ball / DSSSDs

F. Wamers, GSI