Measuring Correlations in Isospin Asymmetric Nuclei

Why and How ?

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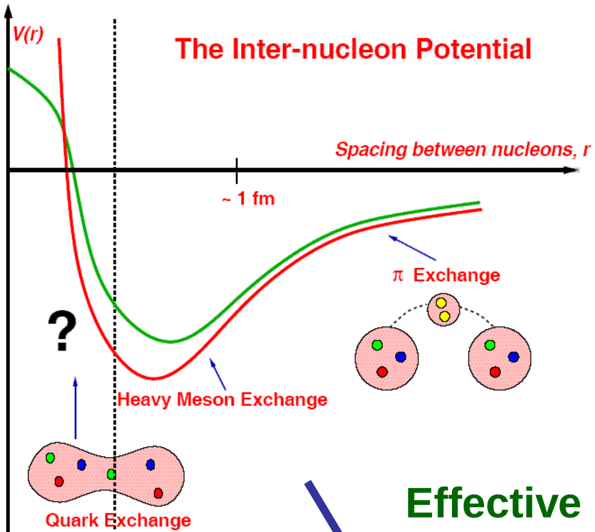
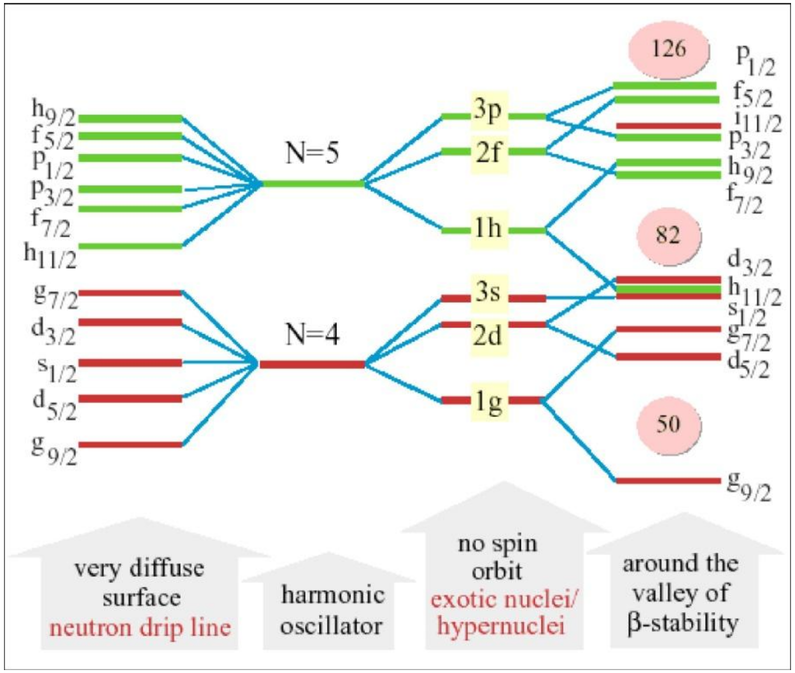
United Kingdom

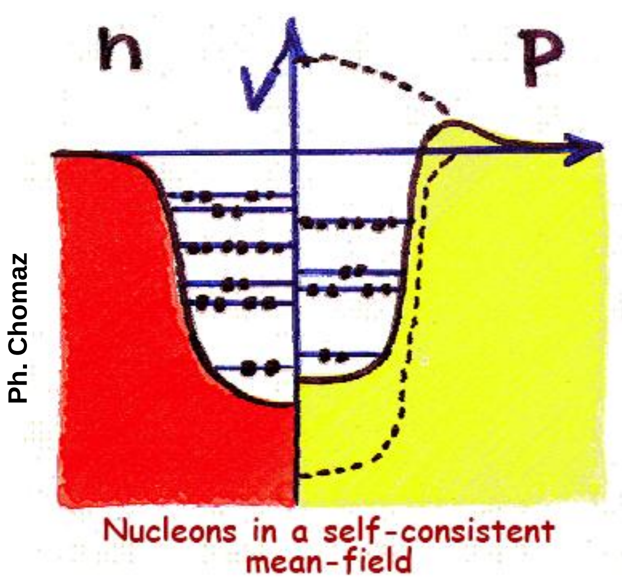
EMMI Programme
The Extreme Matter Physics of Nuclei: From Universal Properties to Neutron-Rich Extremes
GSI, Darmstadt, Germany, 16 April – 11 May, 2012

Mean Field Model of Nuclei





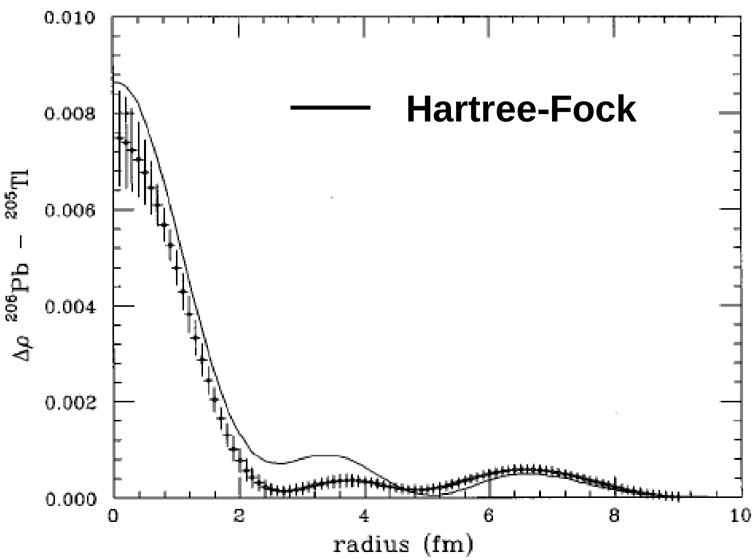
Effective interaction



- **fermion system at low energies**
- **suppression of collisions by Pauli exclusion**
- **independent particle motion**
- **shell structure**
- **mean field approximation**

Validity of Mean Field Concept of Nuclei

J. Cavedon et al., Phys. Rev. Lett. 49 (1982) 978.



Electron Scattering

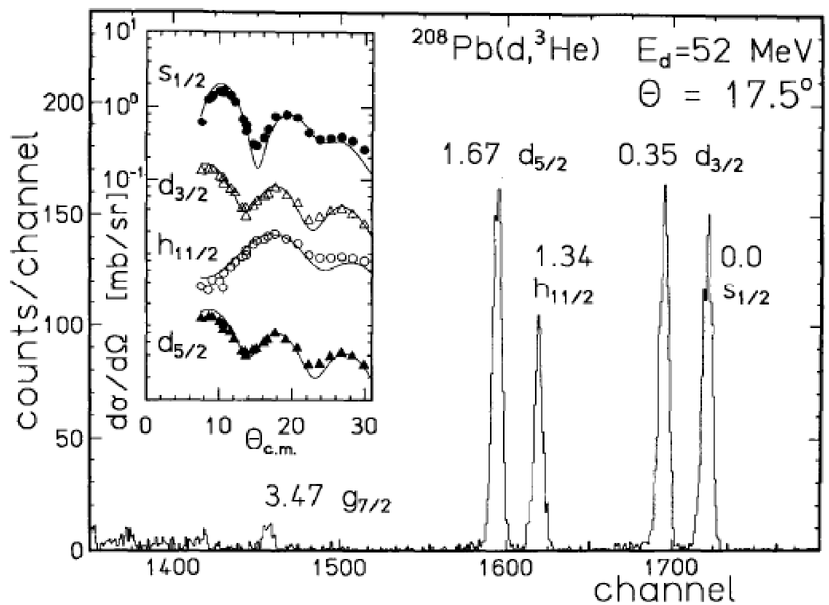
Charge density difference between ^{206}Pb and ^{205}Tl

^{206}Pb and ^{205}Tl differ in IPM by one 3s $_{1/2}$ proton

Transfer Reactions

Only four strong transitions in ^{208}Pb(d,^{3}He)

Pickup from $3s_{1/2}$, $2d_{3/2}$, $1h_{11/2}$ and $1d_{5/2}$



P. Grabmayr et al., Nucl. Phys. A 494 (1989) 244.

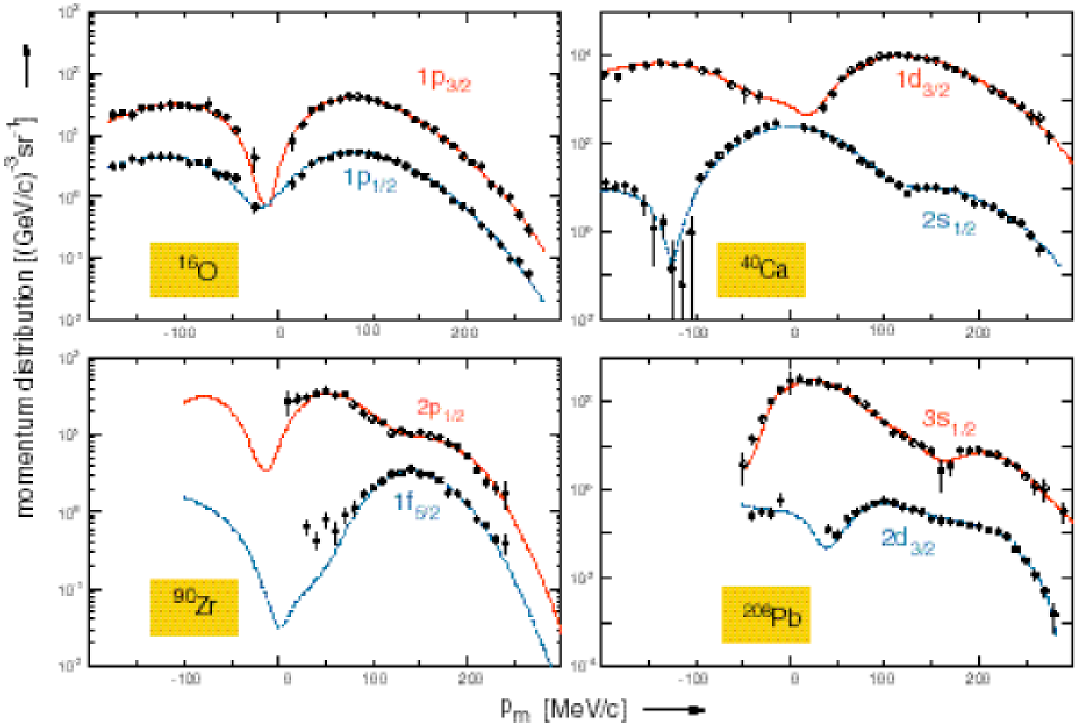
Breakdown of Mean Field Concept

Introduction
Some early (e,e'p) results

Spectroscopic strength with the reaction (e,e'p)

- seventies : pioneering experiments Frascati, Tokyo, Saclay
- eighties : high res. NIKHEF (e,e'p) program for nuclei A=2-209
    - spectral function at low (E_m, p_m)
    - Momentum distributions of valence orbits
- nineties –present : NIKHEF/Mainz/Bates also 2N knockout
- present : JLAB towards higher Q^2, larger p_m , E_m

NIKHEF RESULTS

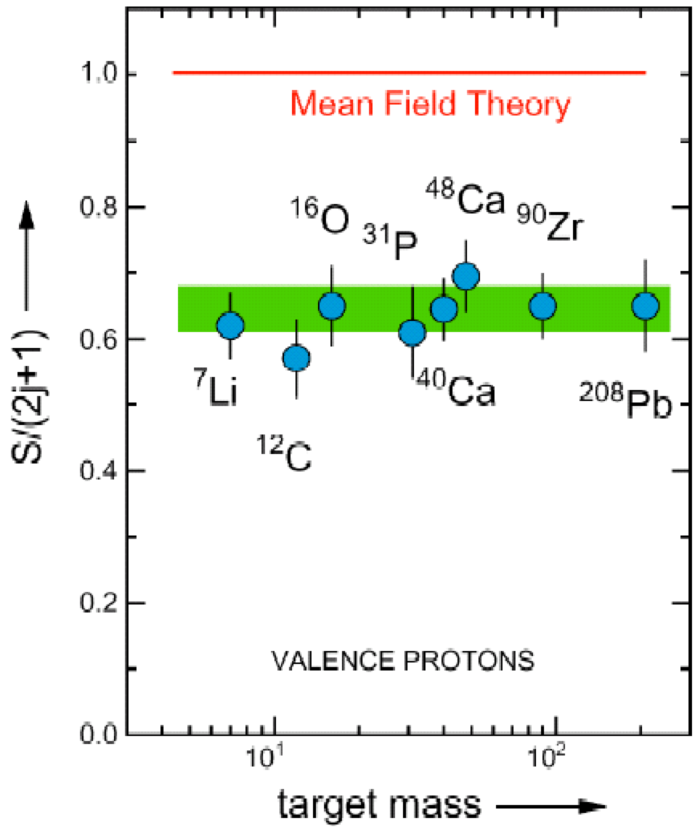


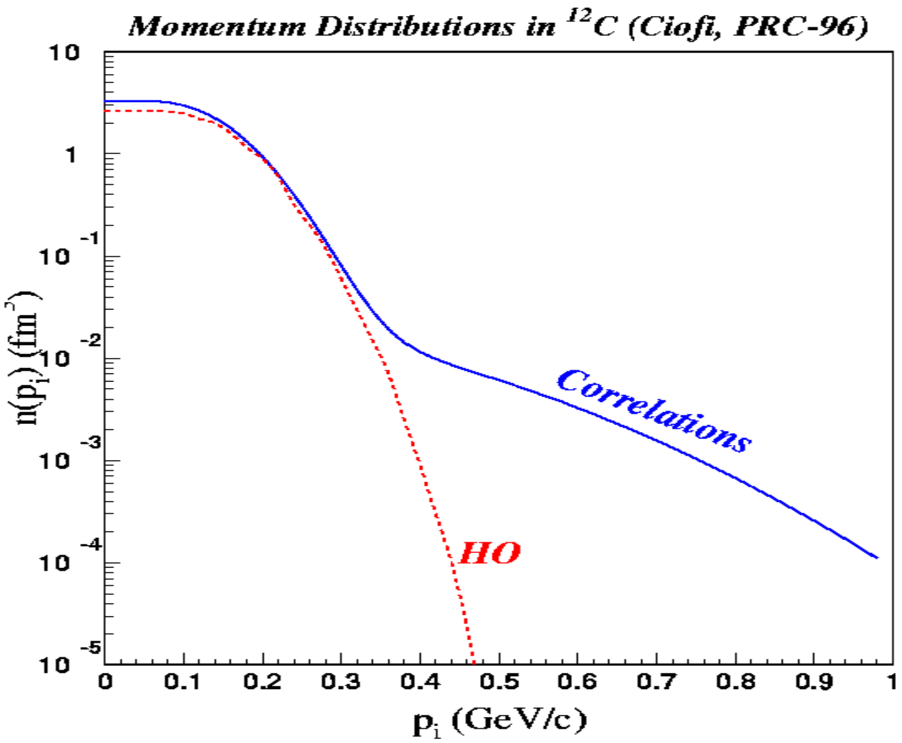
Results for valence orbits in closed-shell nuclei:

Curves scaled by about
0.65
wrt. mean field theory !!

Explanation : Effect of
long-range
and
short-range
correlations

Correlations in (Near-) Symmetric Nuclei

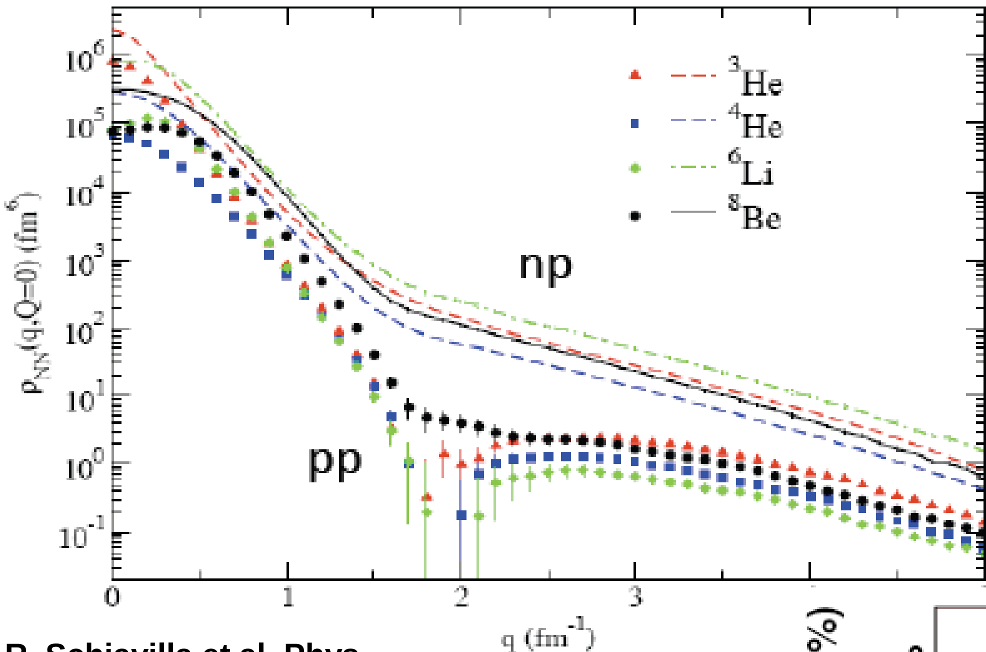




Reduction in spectroscopic strength relative to mean field
-> Long-range, tensor and short-range correlations

Review: W. Dickhoff and C. Barbieri, Prog. Nucl. Part. Sci., 52 (2004) 377.

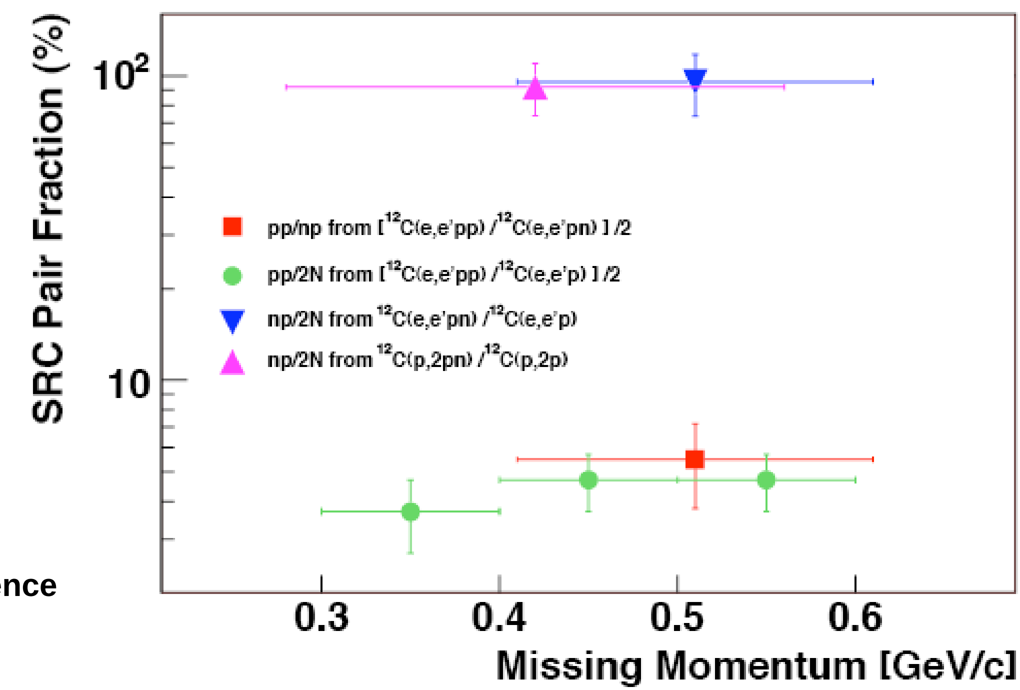
Measurement of High-Momentum Nucleon Pairs



R. Schiavilla et al.,Phys. Rev. Lett. 98 (2007) 132501.

- 20x more pn than pp/nn
- Tensor correlations

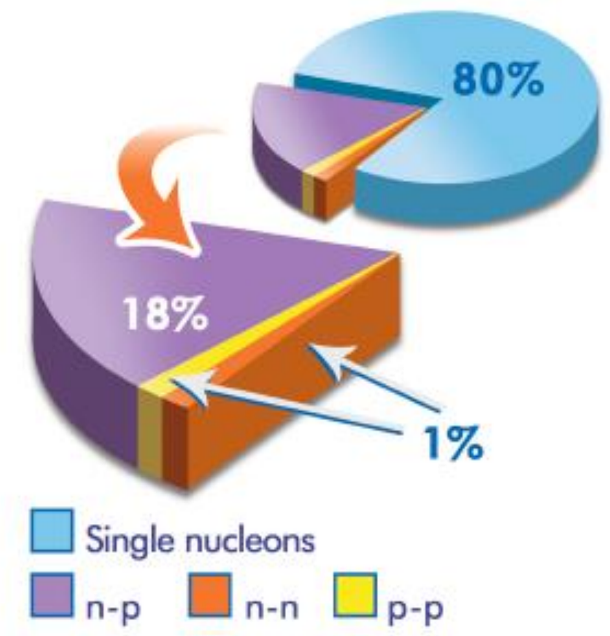
From (e,e’pN) and (p,2pN) data on symmetric nuclei (JLab, BNL, NIKHEF, Mainz …):

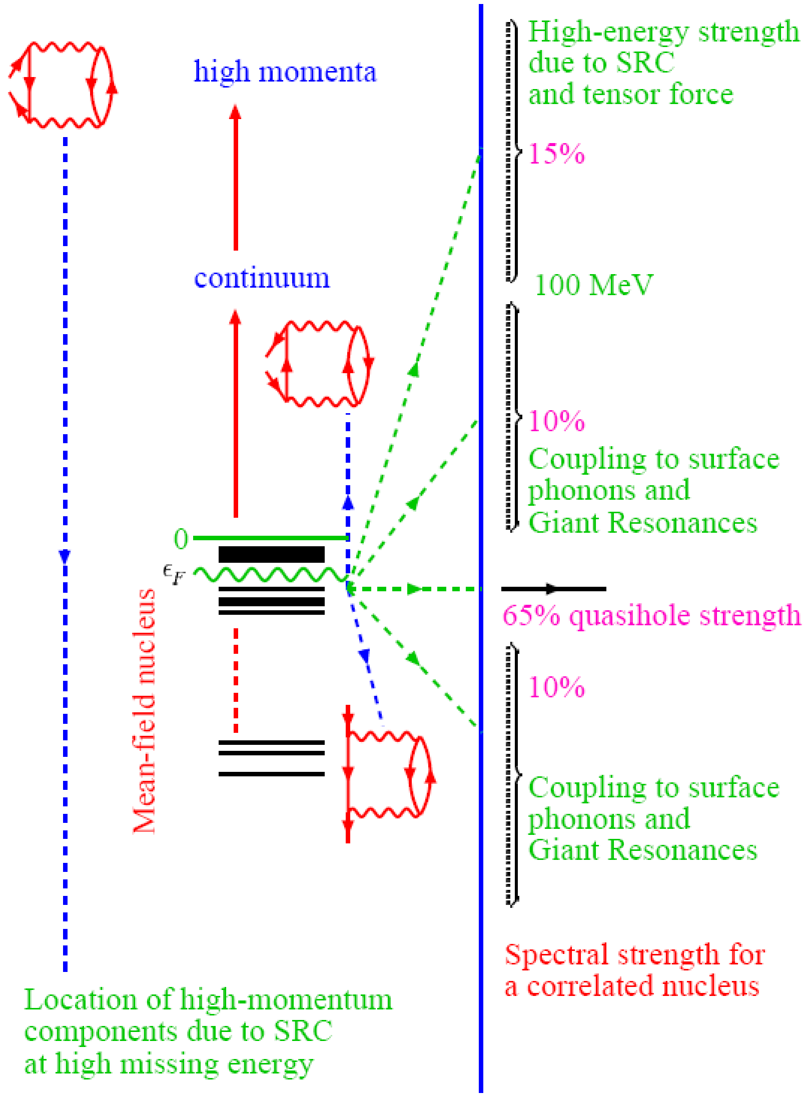


R. Subedi et al.,Science 320 (2008) 1476.

Our Present Knowledge of Proton Behaviour in Symmetric Nuclei

- 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:

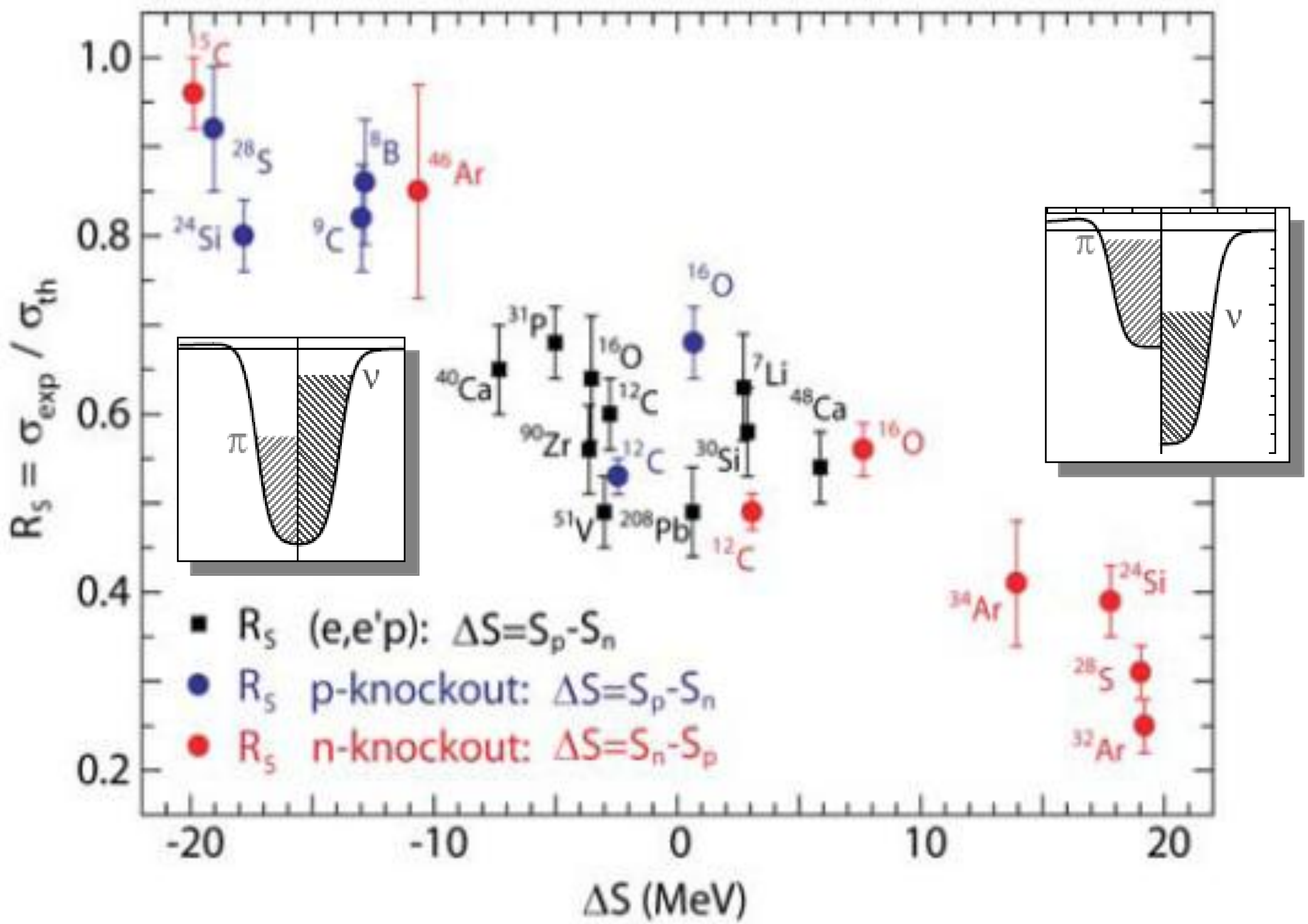




W. Dickhoff and C. Barbieri, Prog. Nucl. Part. Sci. (2004)

Correlations in Asymmetric Nuclei

1n Removal Reactions

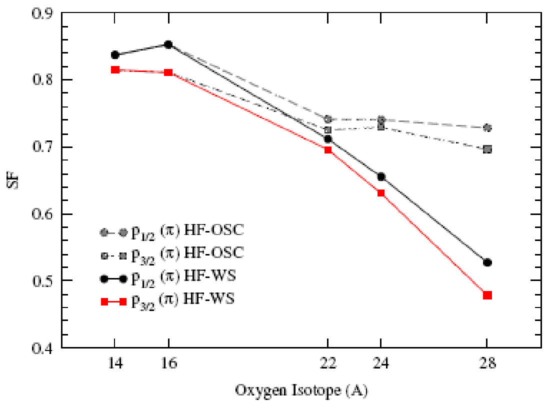


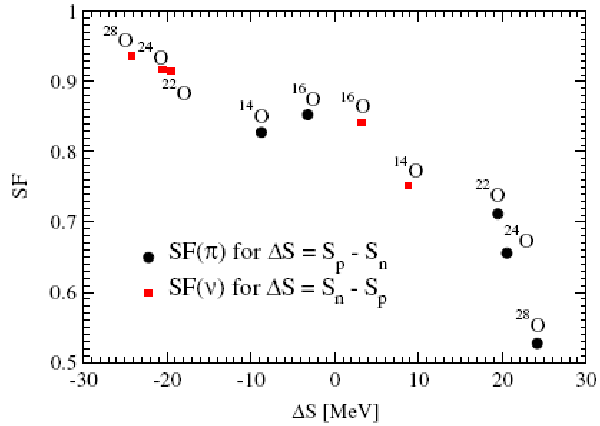
A. Gade et al., Phys. Rev. C 77 (2008) 044306.

PRL 107, 032501 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

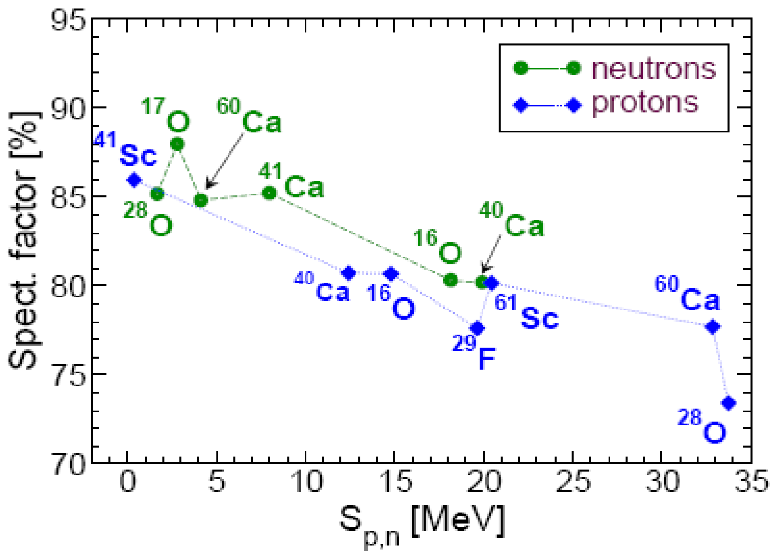
Quenching of Spectroscopic Factors for Proton Removal in Oxygen Isotopes

Ø. Jensen,[1] G. Hagen,[2,3] M. Hjorth-Jensen,[1] B. Alex Brown,[4,5] and A. Gade[4,5]





Coupled-cluster calculation N³LO
including coupling to scattering states above the neutron separation threshold

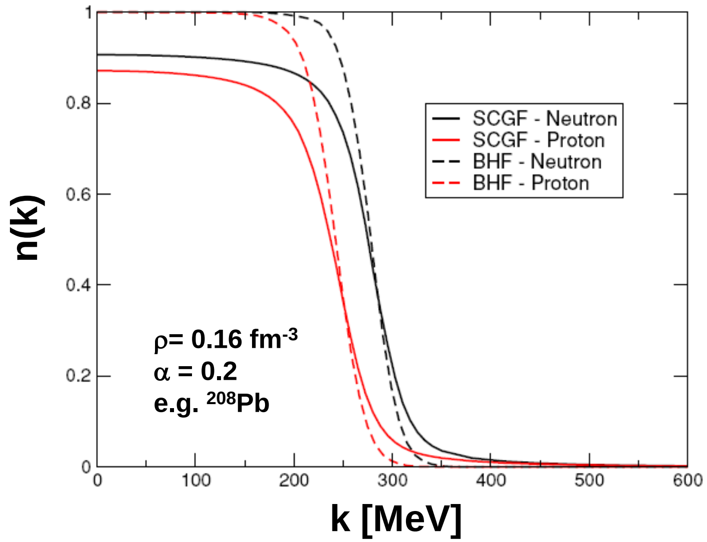


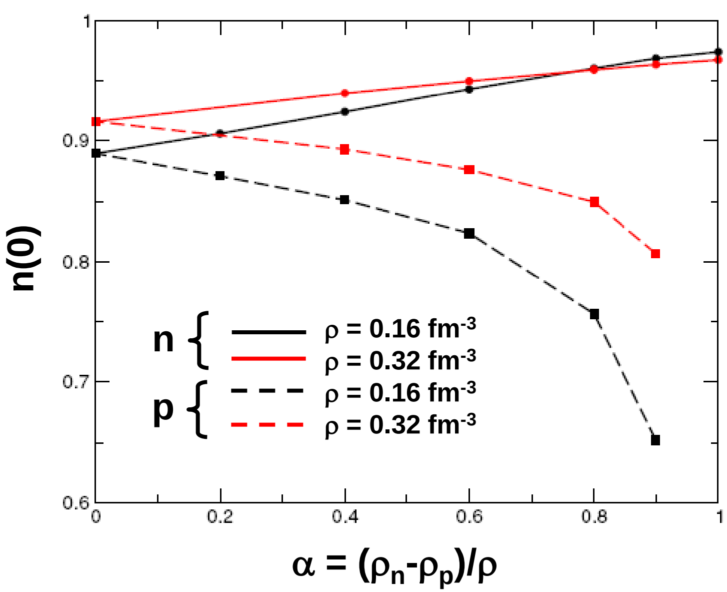
C. Barbieri et al.,
arXiv:0901.1920v1 (2009).

SCGF method using chiral N3LO force

SRC in Isospin Asymmetric Matter

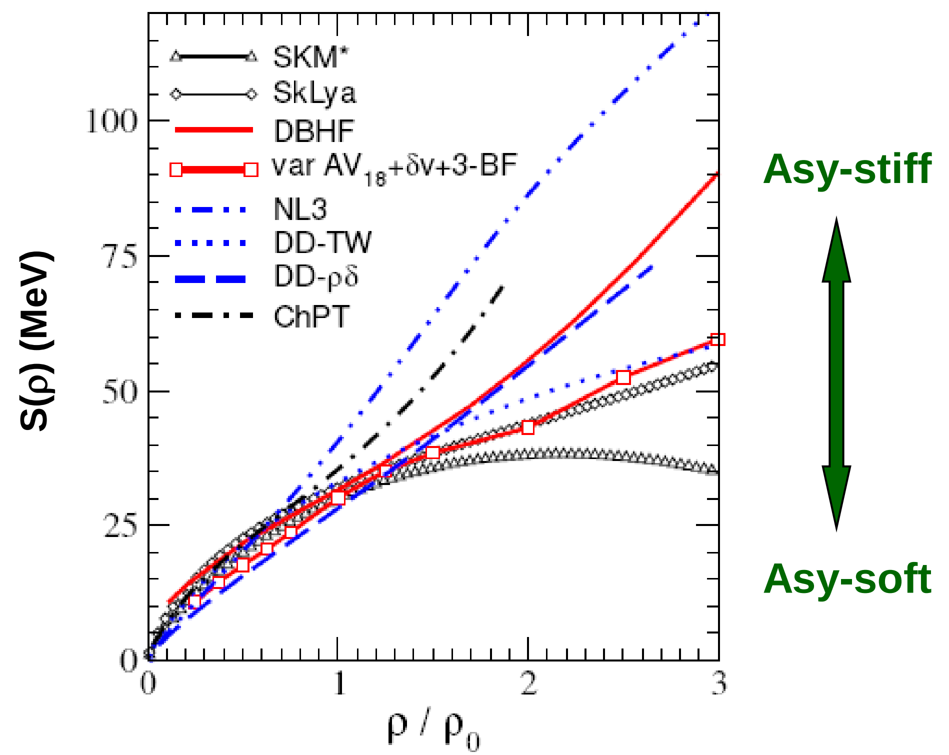
Brueckner-Hartree Fock (BHF)
Self-Consistent Green's Function (SCGF)





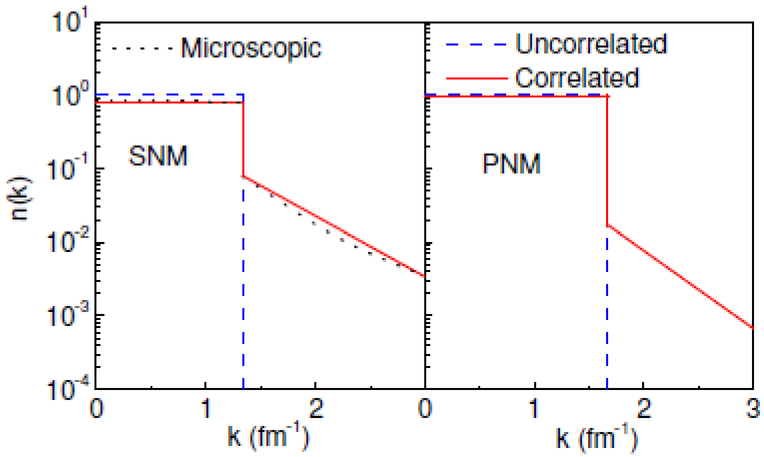
T. Frick et al. PRC 71 (2005) 014313.

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2.S(\rho)$$



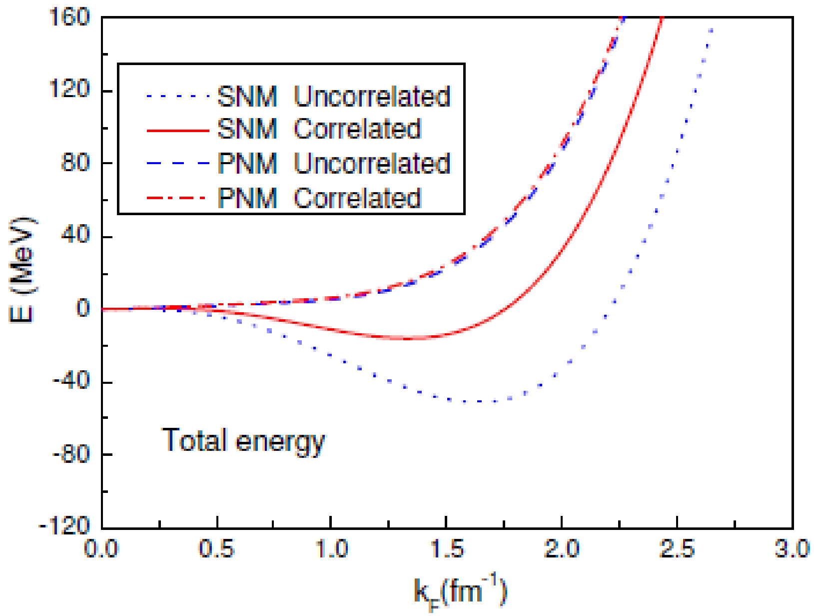
Dependence of correlations on density, isospin asymmetry etc. is vital to understand asymmetric matter: EOS, neutron stars etc.

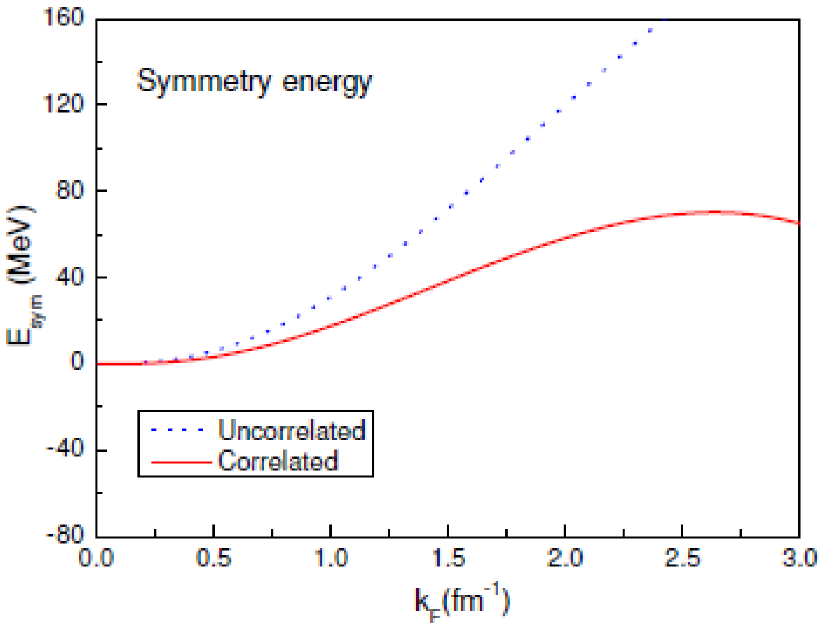
Effect of Isospin Dependence of SRC on Nucleonic EOS



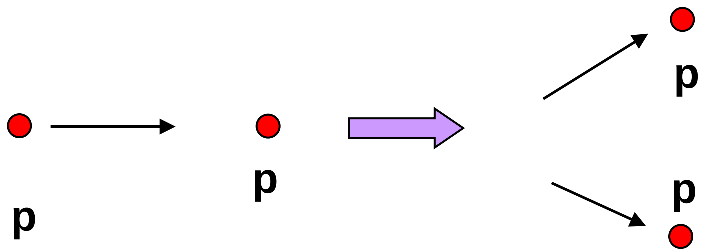
- Constrained to match measured isospin dependence of SRC
- Softening of symmetry energy

C. Xu and B.-A. Li, arXiv:1104.2075v1
A. Carbone and A. Rios, arXiv.1111.0797v2

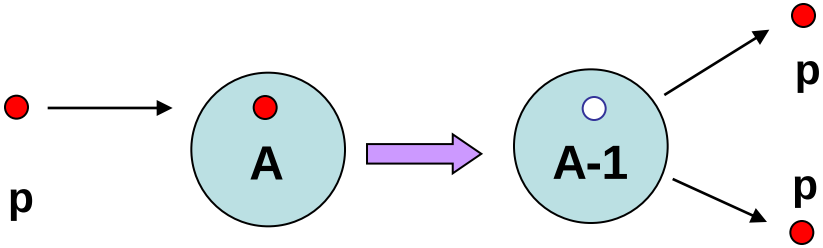




Probing Nucleon-Nucleon Correlations Experimentally

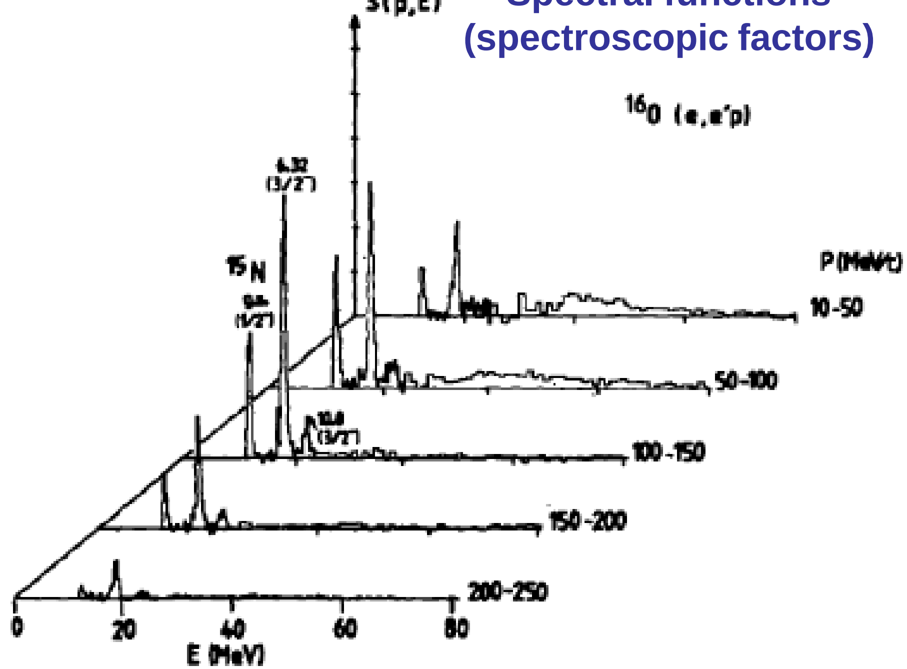


Free NN scattering



In-medium NN scattering

Spectral functions (spectroscopic factors)

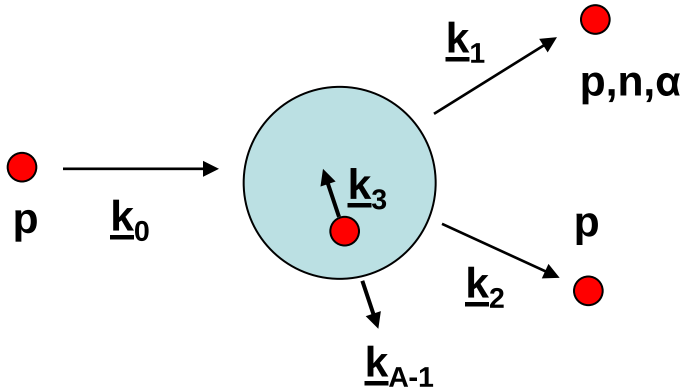


QFS most direct probe of the properties of a nucleon inside the nuclear medium:

- **validity of mean field/single particle concepts**
- **role of correlations, e.g. LRC, SRC, Tensor**
- **in-medium nucleon-nucleon interaction**

Quasifree Scattering Reaction: Normal Kinematics

High energy protons, E_p = 100-1000 MeV
- simplify reaction mechanism: impulse approximation
- minimise final state interactions: spectator nucleons



Measure k_1 and k_2.
k_{A-1} not measured directly.

Nuclear recoil momentum :

$$k_{A-1} = k_0 - k_1 - k_2 = -k_3$$

Separation energy of knocked-out nucleon

$$E_S = E_0 - E_1 - E_2 - \frac{k_{A-1}^2}{2(A-1)}$$

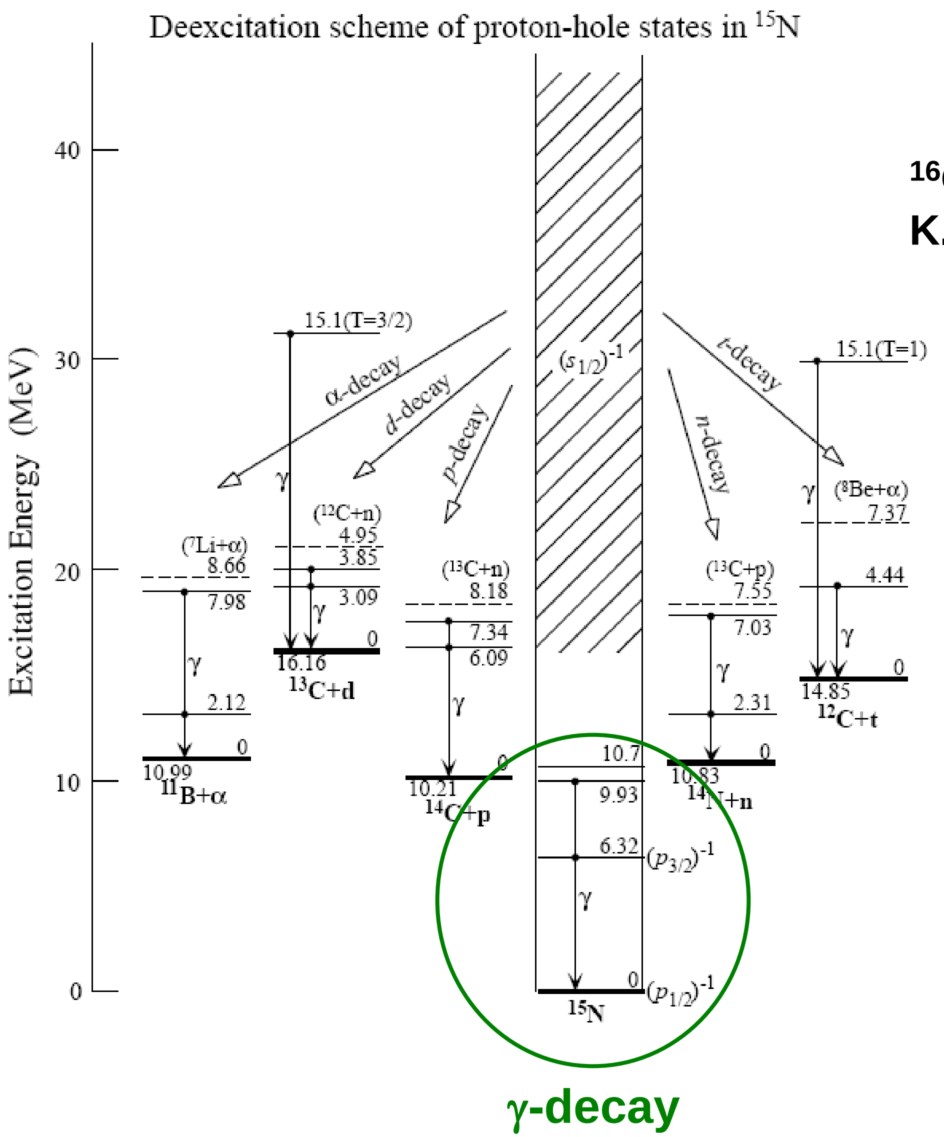
Distortion of the incoming and outgoing nucleon wavefunctions (from final state interactions, multiple scattering):

Distorted Wave Impulse Approximation

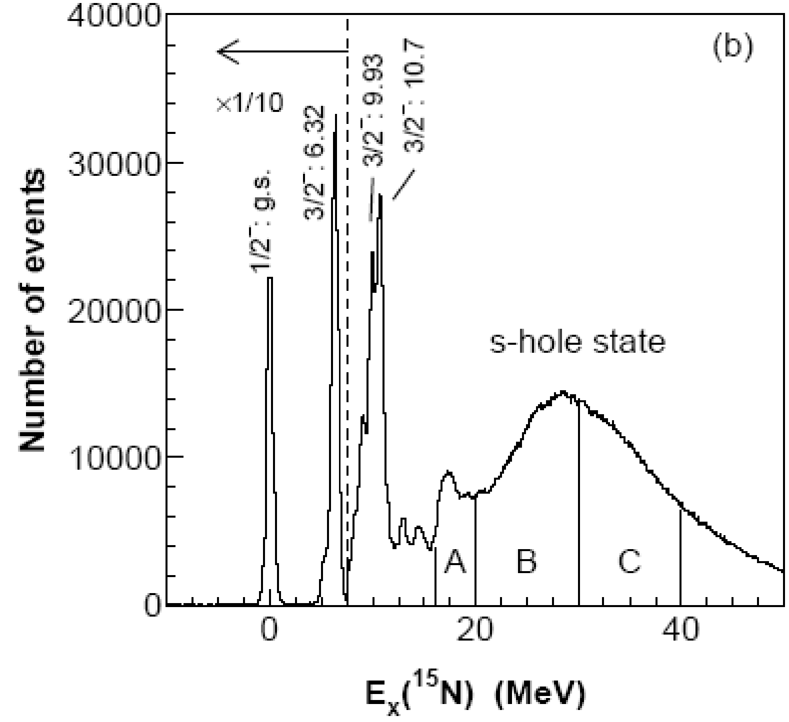
$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE} = \underbrace{S_3}_{\text{spectroscopic factor}} F_k \underbrace{\frac{d\sigma_{pp}}{d\Omega}\left(E_0, \theta, P_{eff}\right)}_{\text{free n-n cross-section}} \underbrace{G\left(\vec{k}_3\right)}_{\text{distorted momentum distribution}}$$

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

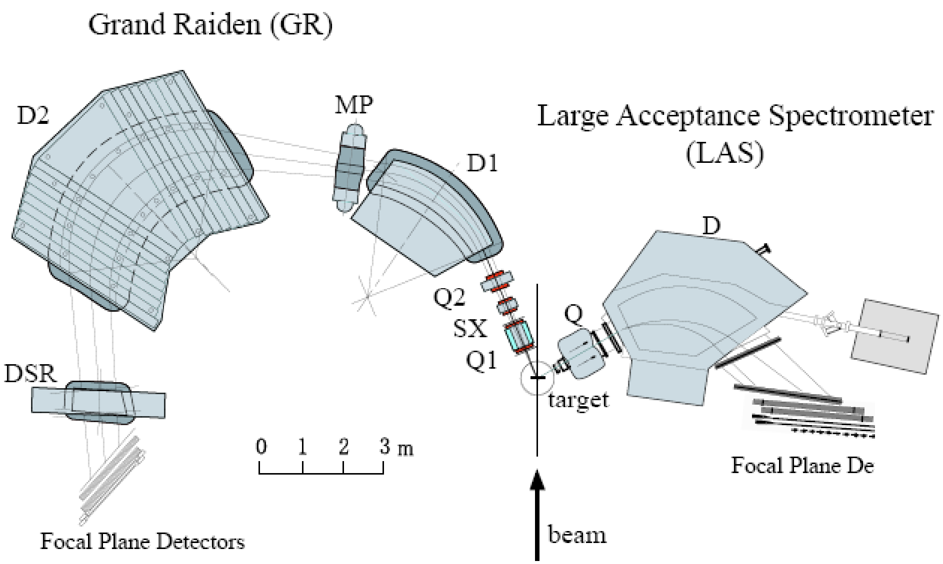
States Populated in Quasifree Hadronic Scattering



^{16}O(p,2p)^{15}N, E_{beam} = 392 AMeV
K. Kobayashi et al., arXiv:nucl-ex/0604006

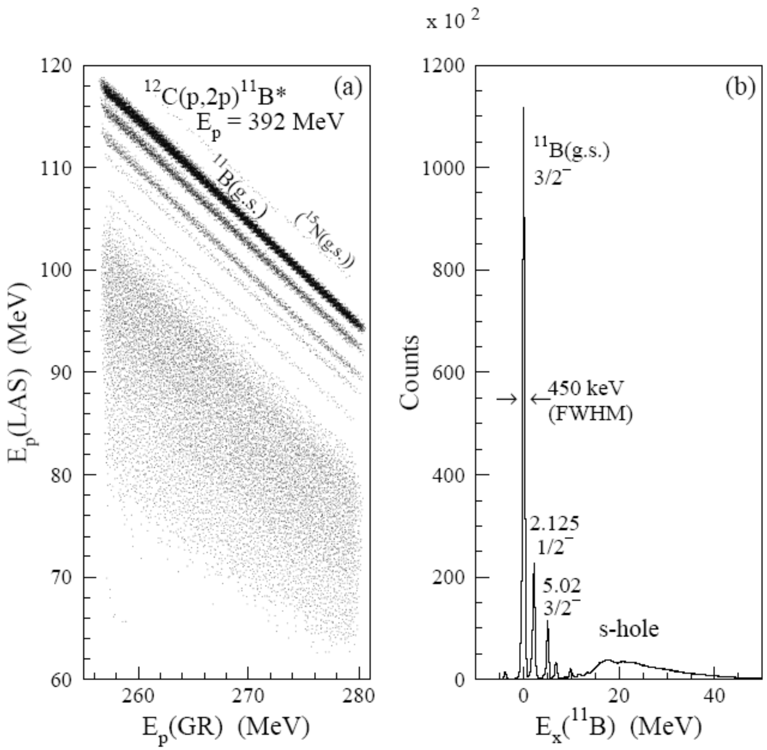


Recent Experiment in Normal Kinematics: $^{12}C(p,2p)^{11}B$



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

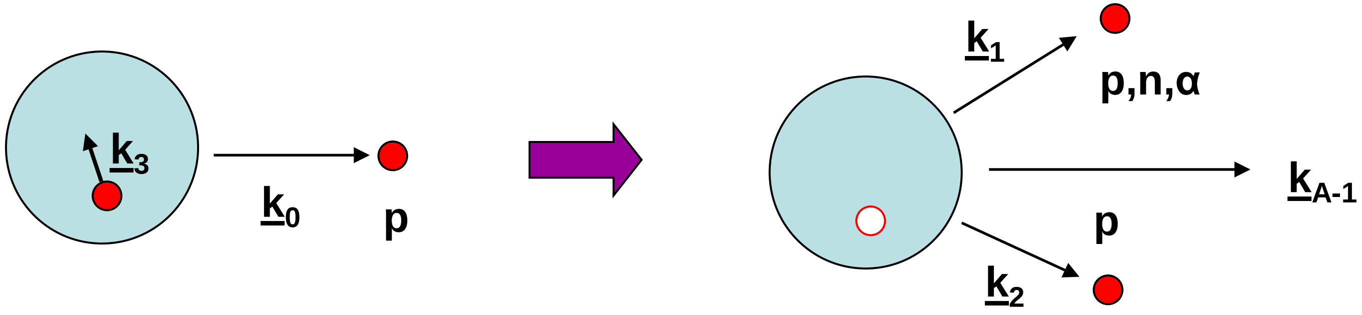


RCNP, Osaka
E_p = 392 MeV
Two spectrometer measurement
Energy resolution (FWHM) ≈ 450 keV

Quasifree Scattering Reaction: Inverse Kinematics

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

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



Can now 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 -see next slide

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

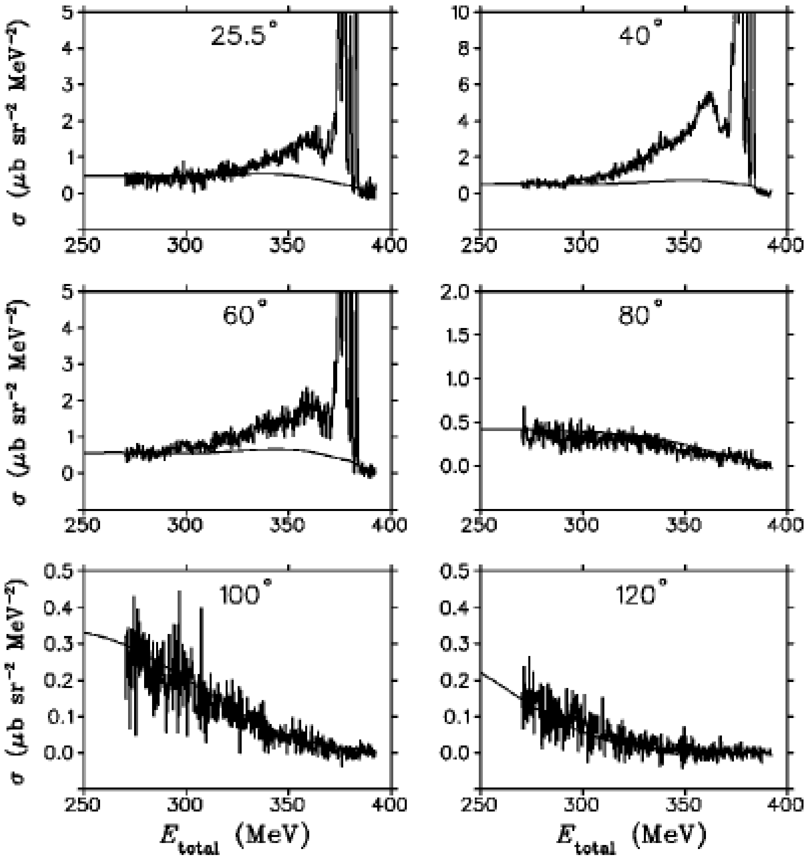
$$k_3 = \frac{A-1}{A} k_A - k_{A-1}$$

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

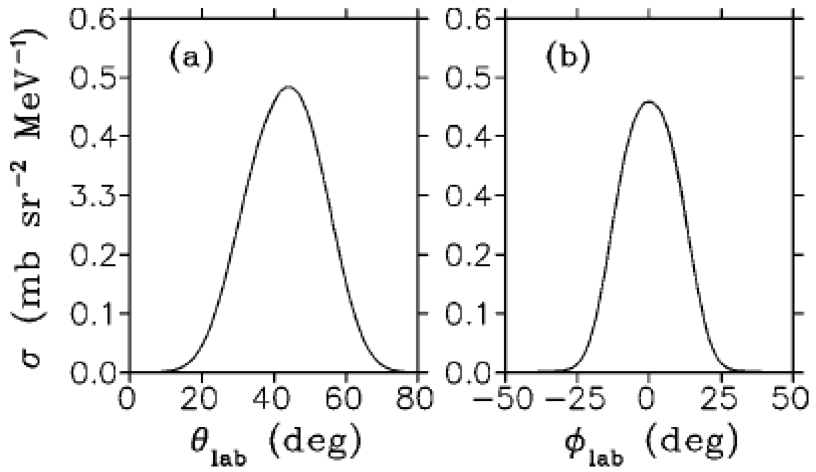
c.f. one-nucleon removal reactions with light-ion targets

Advantages of Inverse Kinematics : Rescattering Contributions

$^{40}Ca(p,p'p'')$ E_p = 392 MeV



DWIA calculations

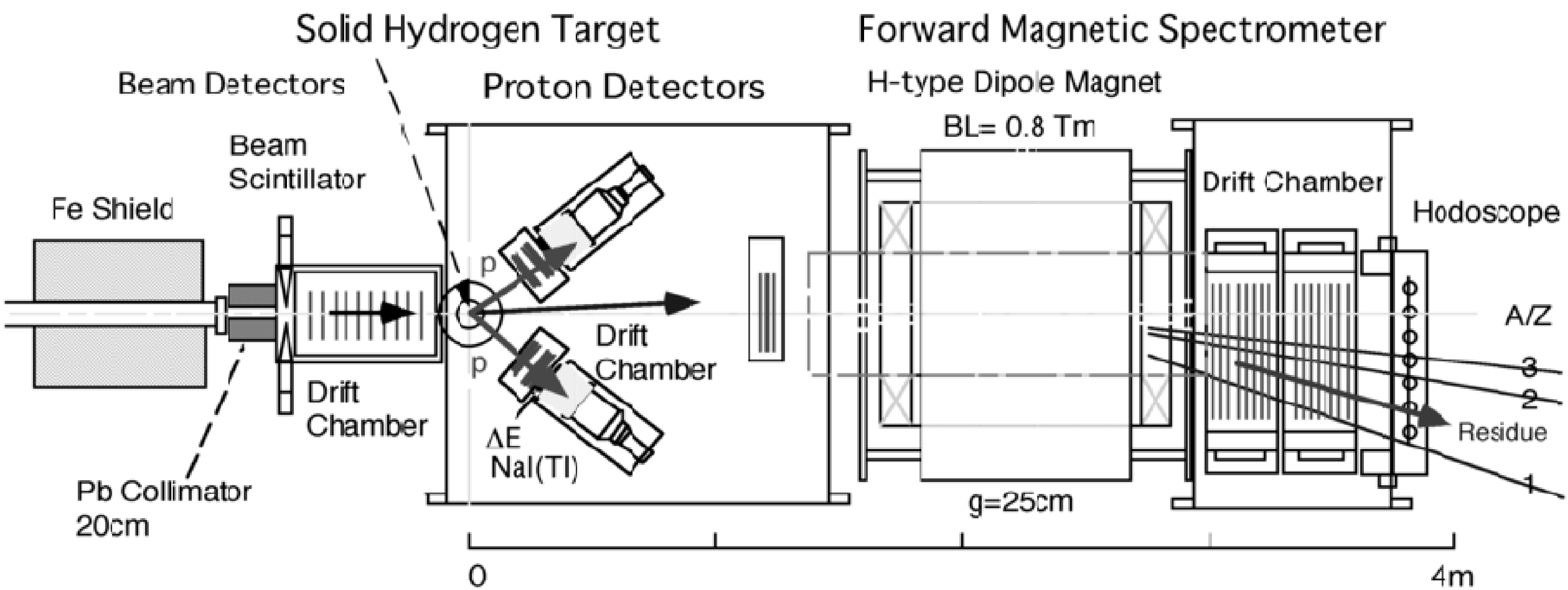


In-plane **Out-of-plane**

Two spectrometer measurement
LAS + Grand Raiden at RCNP, Osaka

A.A. Cowley et al., Phys. Rev. C 57 (1998) 3185.

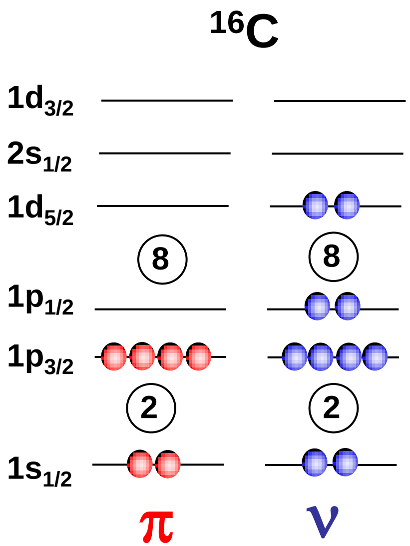
Experiments at HIMAC: $^{9\text{-}16}$C(p,2p) @ 250 AMeV

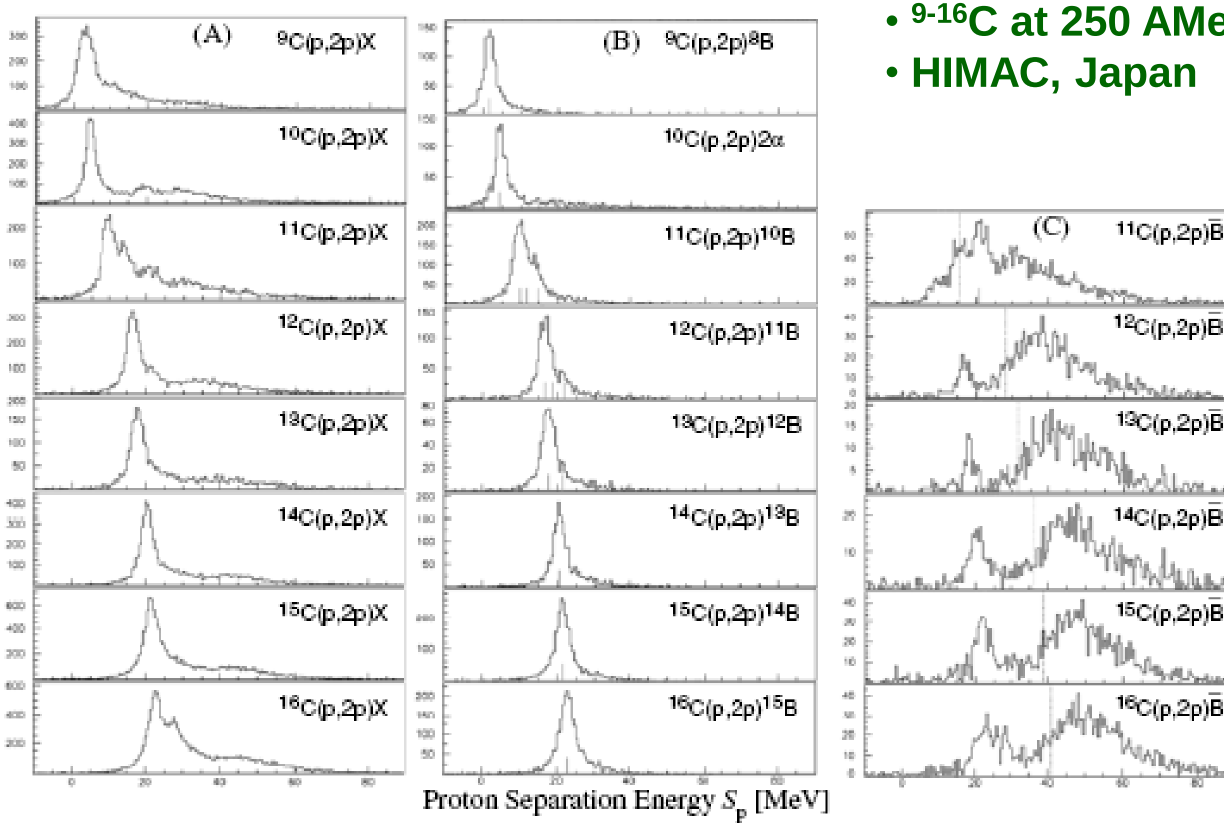


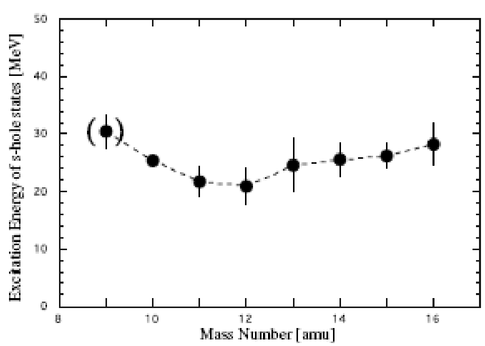
T. Kobayashi et al.

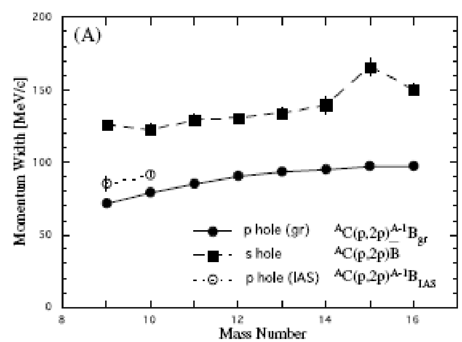
Spectroscopy of Valence and Deeply Bound Nucleons

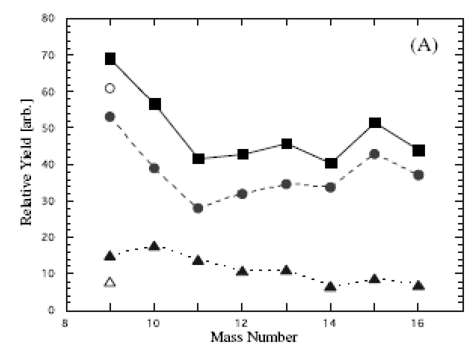
- $^{9-16}$C at 250 AMeV
- HIMAC, Japan





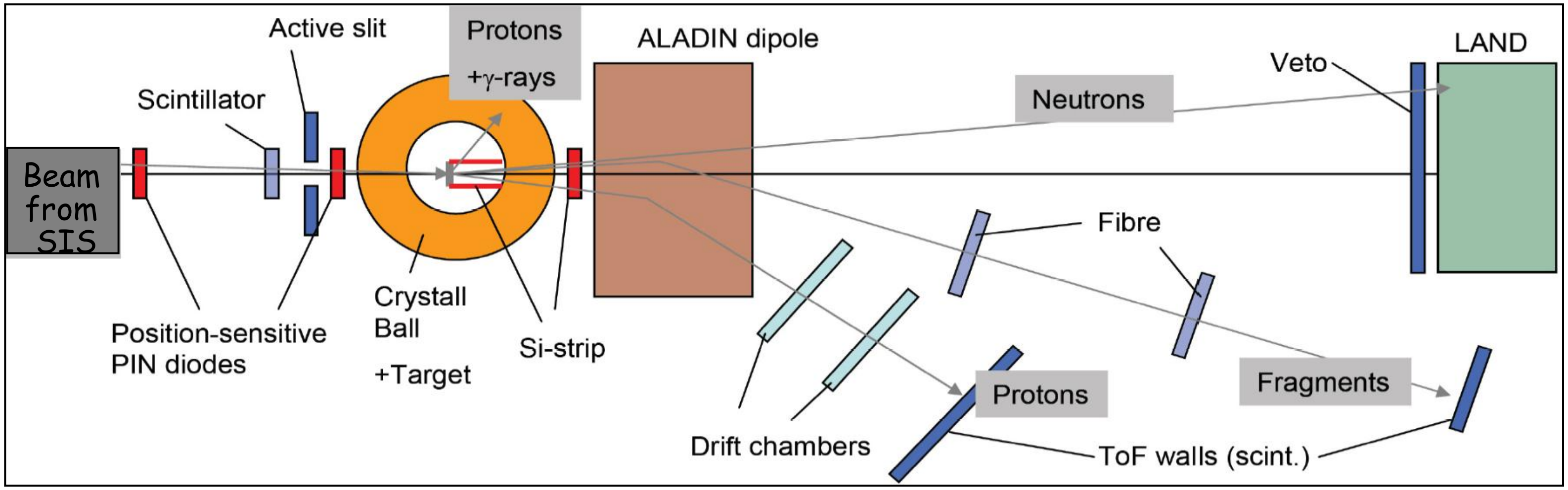






T. Kobayashi et al., Nucl. Phys. A 805 (2008) 431c.

Experiments at GSI: LAND/R3B



- kinematical complete measurement of:
  - (p,pn), (p,2p), (p,pd), (p,α), ... reactions
- redundant experimental information:
  - kinematical reconstruction from proton momenta
  - plus gamma rays, invariant mass, recoil momentum
- sensitivity not limited to surface:
  - spectral functions
  - knockout from deeply bound states
  - cluster knockout reactions

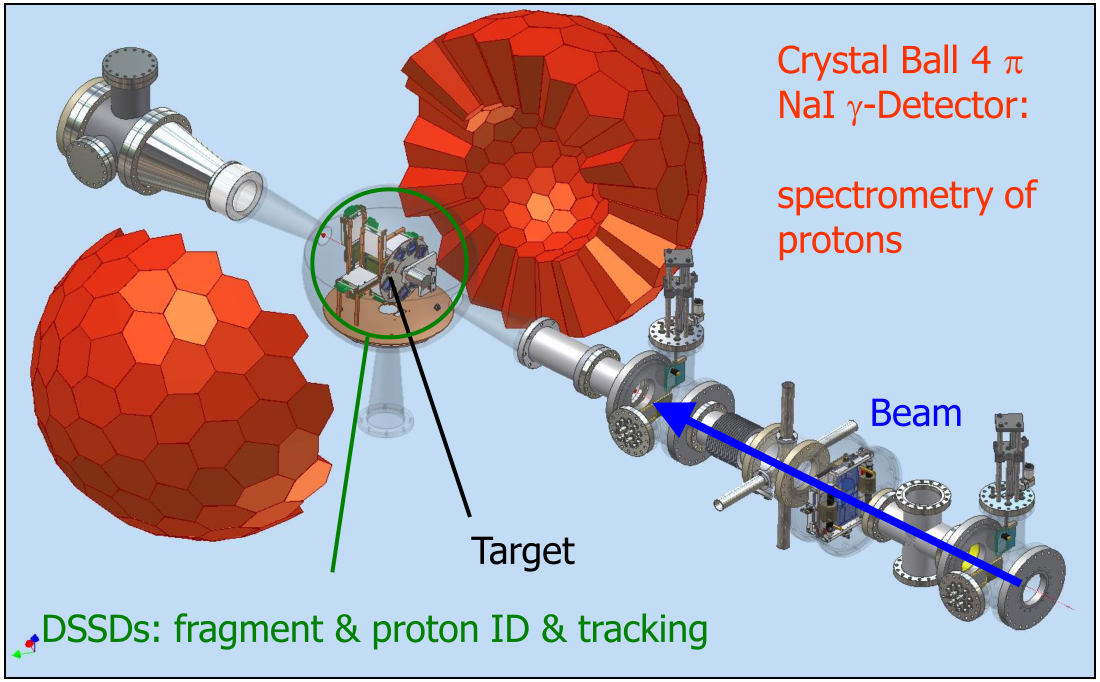
Experiments so far:

- ^{12}C
- ^{17}Ne
- O isotopic chain

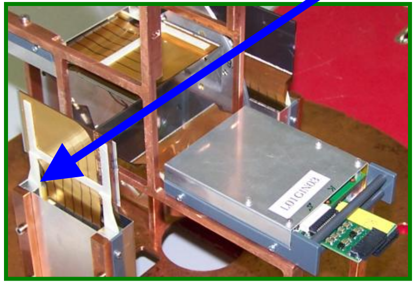
All use C/CH2 targets

Target Recoil Detector for QFS Experiments

LAND setup: Detectors around the target



New: DSSDs for proton tracking

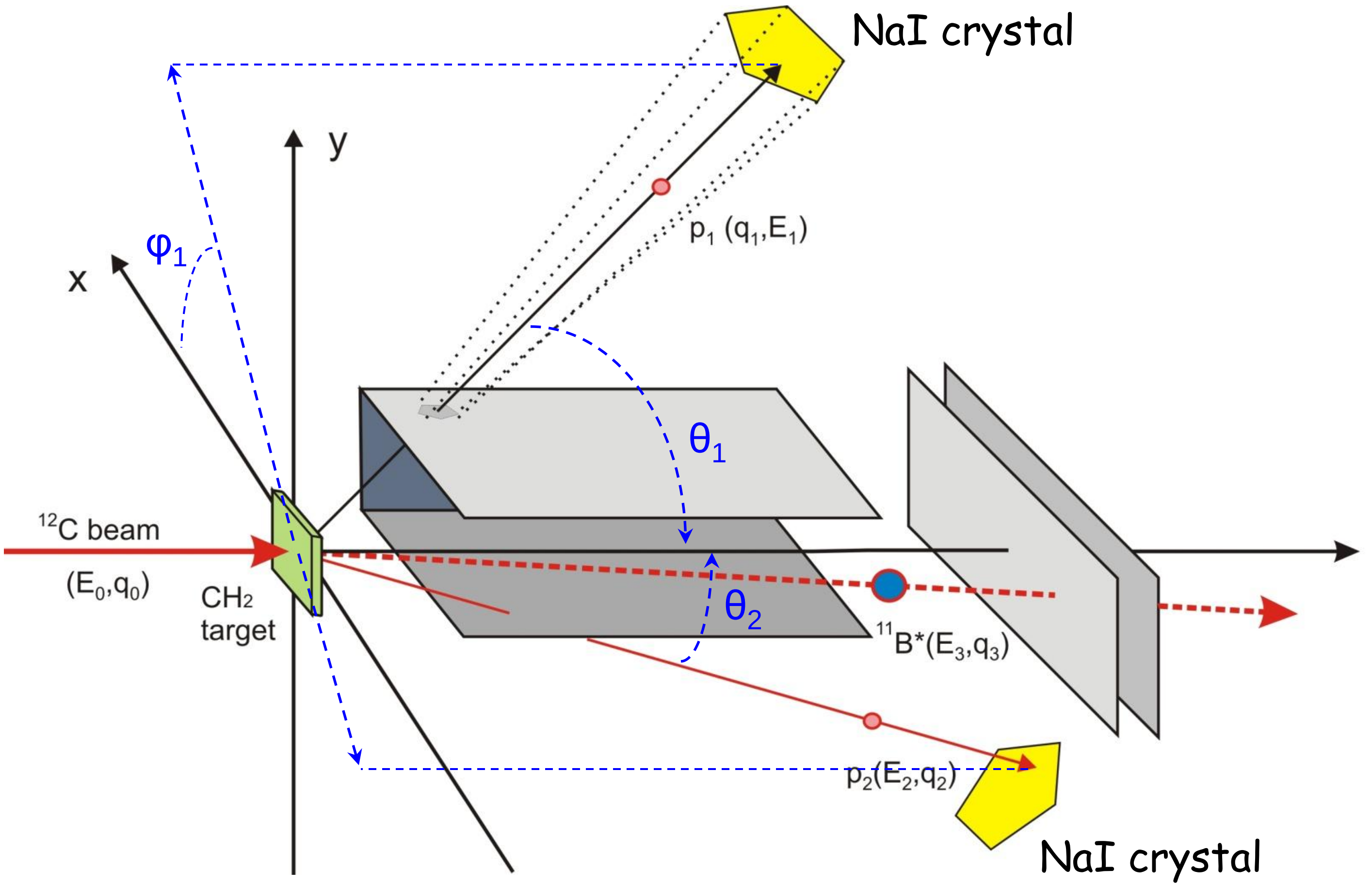


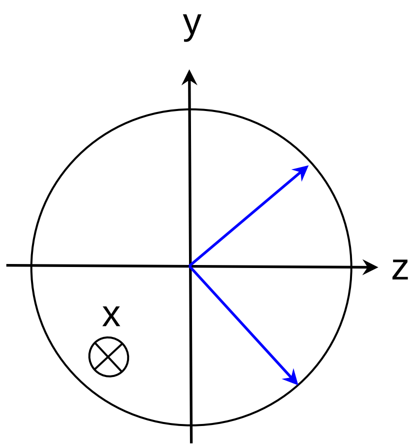
- 4 box detectors for proton tracking
- polar angle coverage ≈ 15°≤ θ ≤ 80°
- resolution: Δx ~ 100 μm; ΔE ~ 50 keV
- range: 100 keV < E < 14 MeV
- 2 in-beam detectors for tracking & ID of fragments and protons

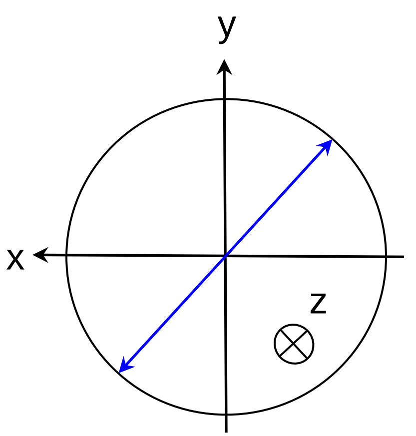
New: Crystal Ball for proton spectrometry

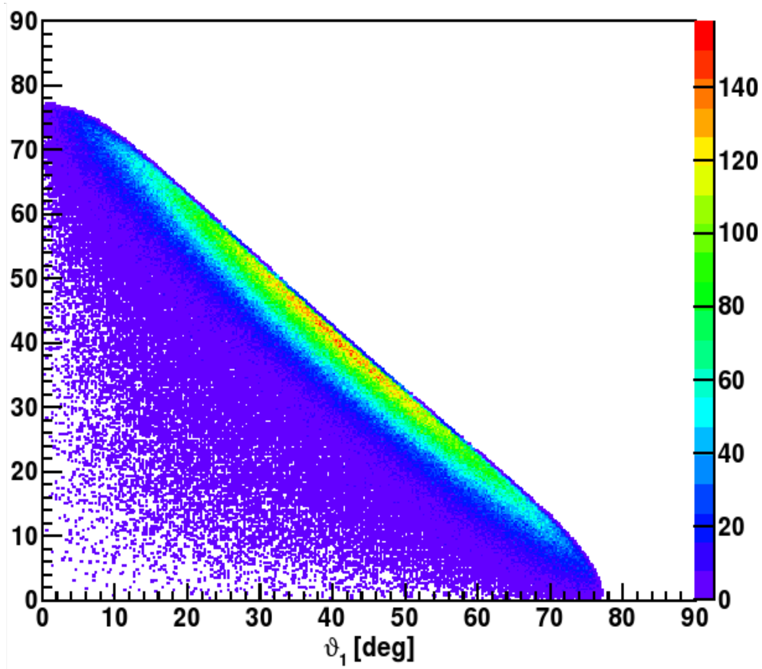
- 4π gamma detector (*1980 - ...)
- 162 NaI(Tl) crystals of 20 cm length
- New: Measure energy of recoil protons with additional readout of the forward 64 crystals (~ 2π) !

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

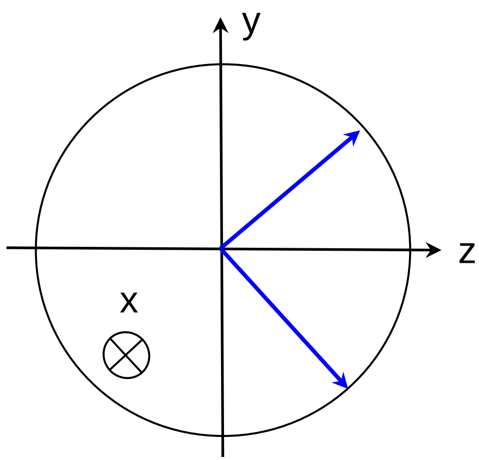


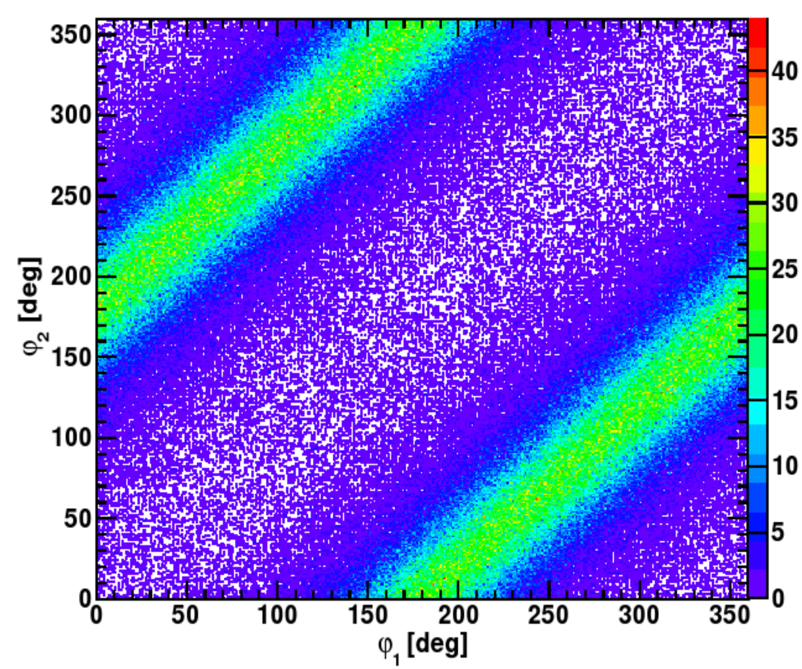




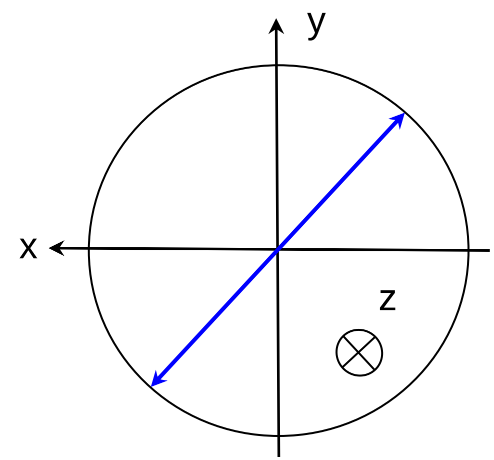


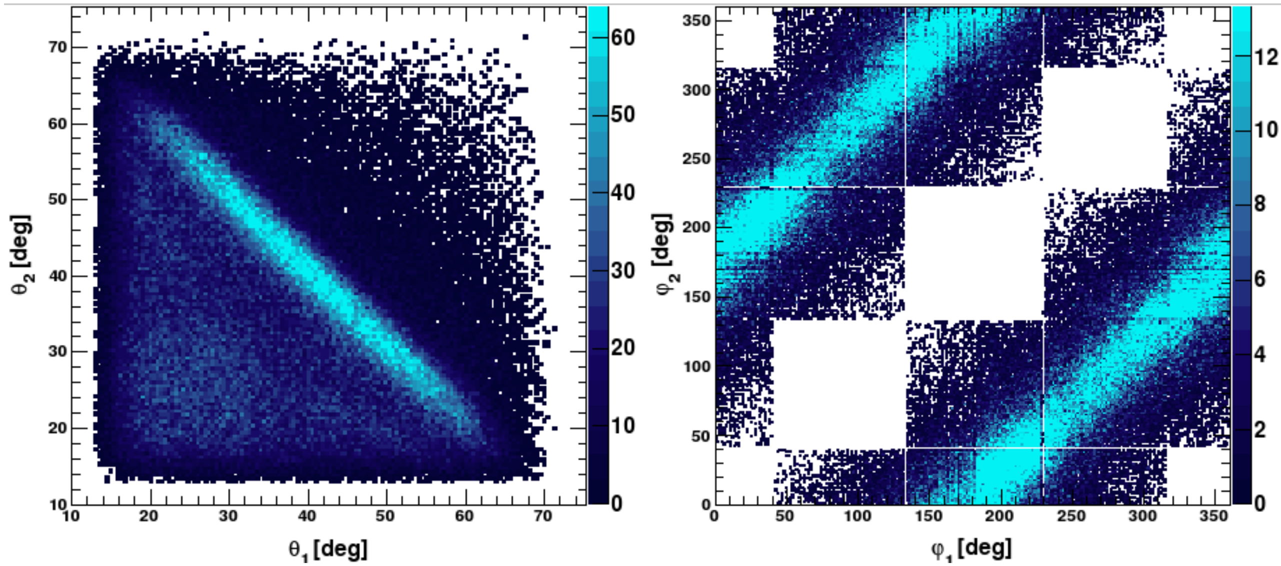
(a) Correlation of zenith angles



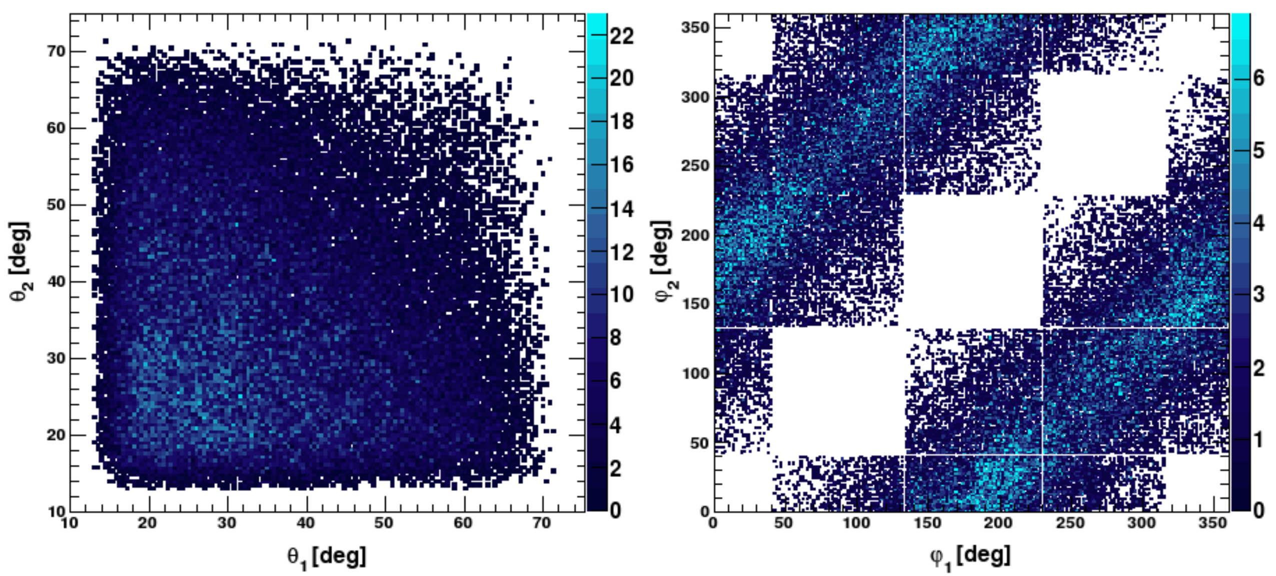


(b) Correlation of azimuth angles

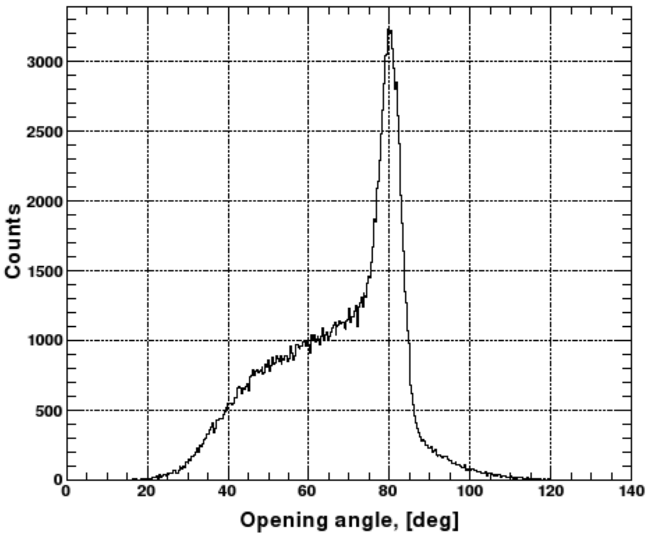


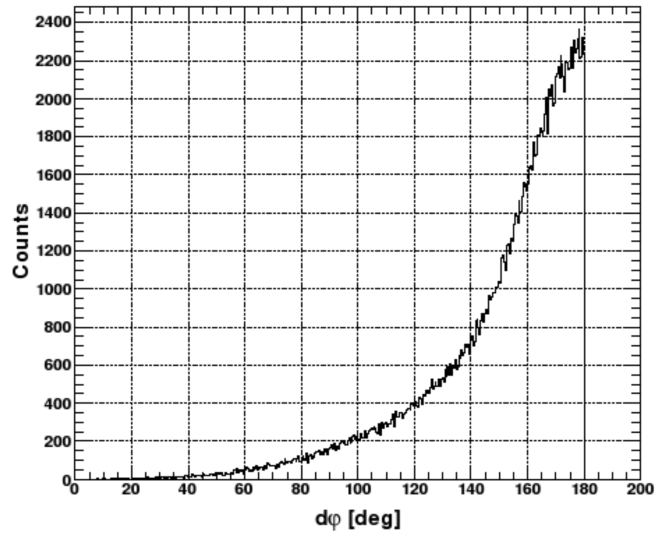


CH2 target

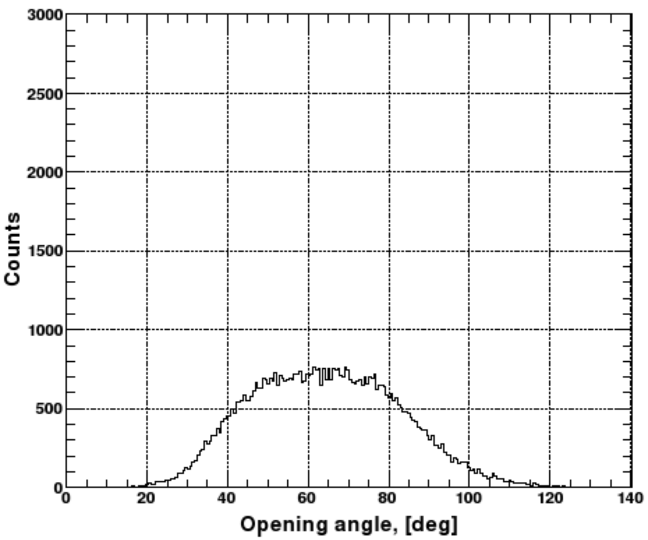


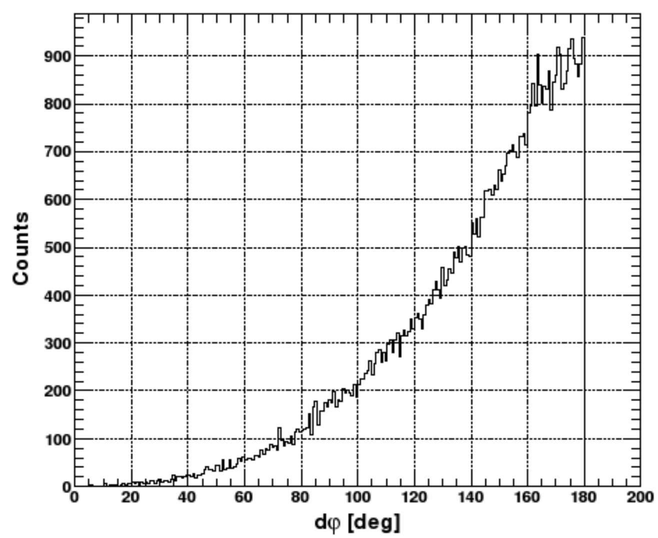
Carbon target





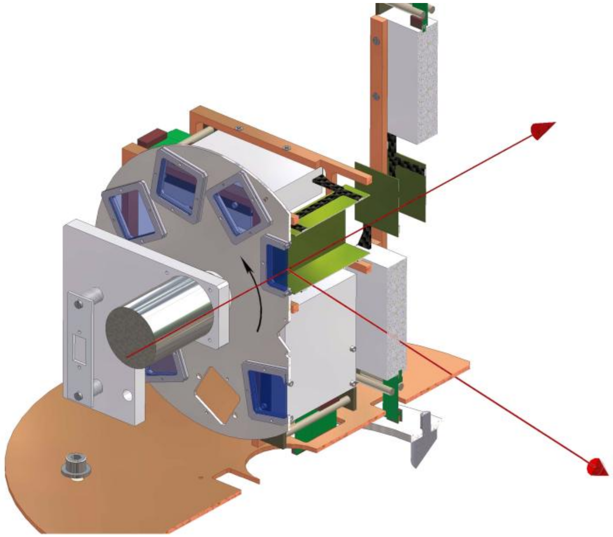
CH2 target

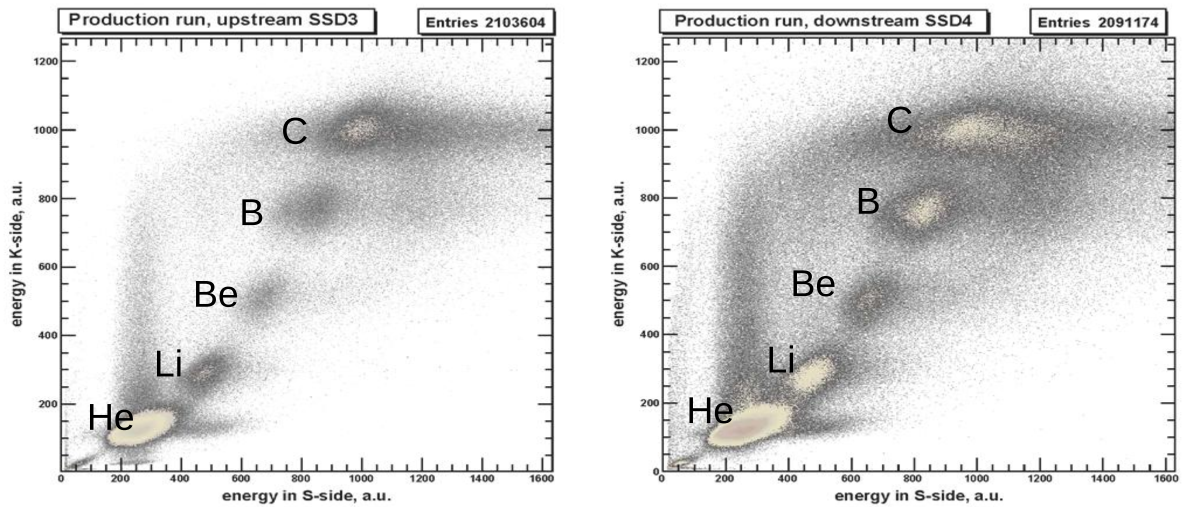


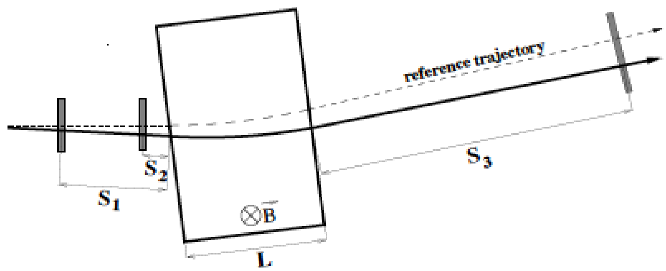


Carbon target

Charge identification in two in-beam DSSDs

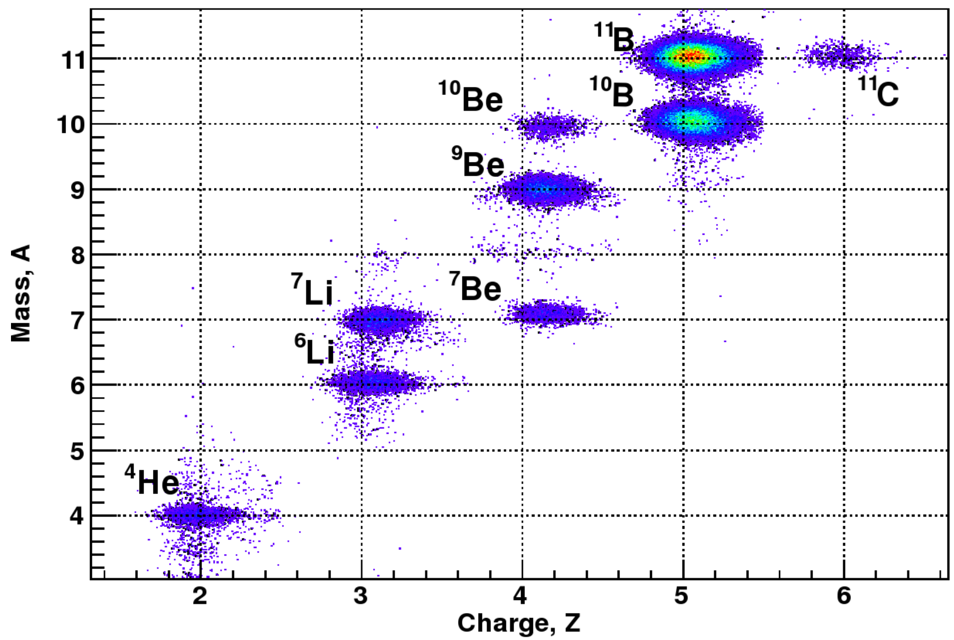






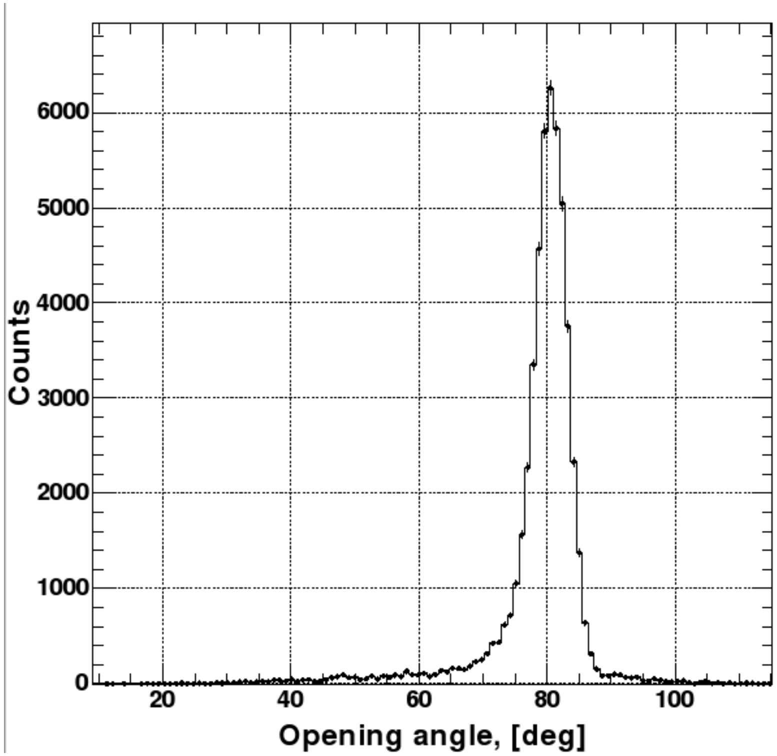
$$(B\rho)_0 = \frac{m_u c}{e}\frac{A_0}{Z_0}\beta_0\gamma_0 = 3.10716\frac{A_0}{Z_0}\beta_0\gamma_0$$

$$\frac{d(B\rho)}{(B\rho)_0} = \frac{1}{c_{13}}\left(x_3 - a_{13}x_1 - b_{13}\frac{x_2 - x_1}{S_1 - S_2}\right)$$



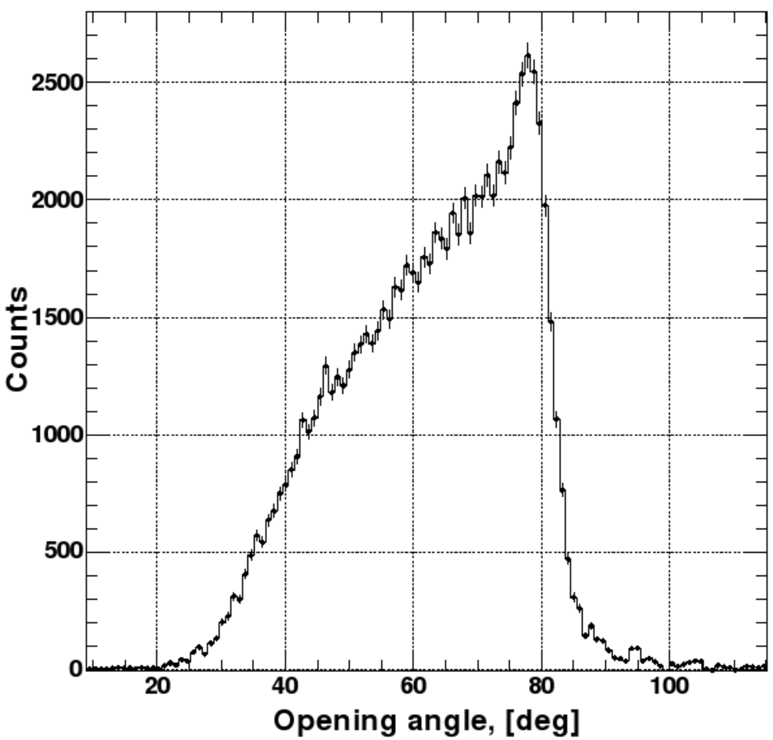
Hydrogen target (BG subtracted)

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



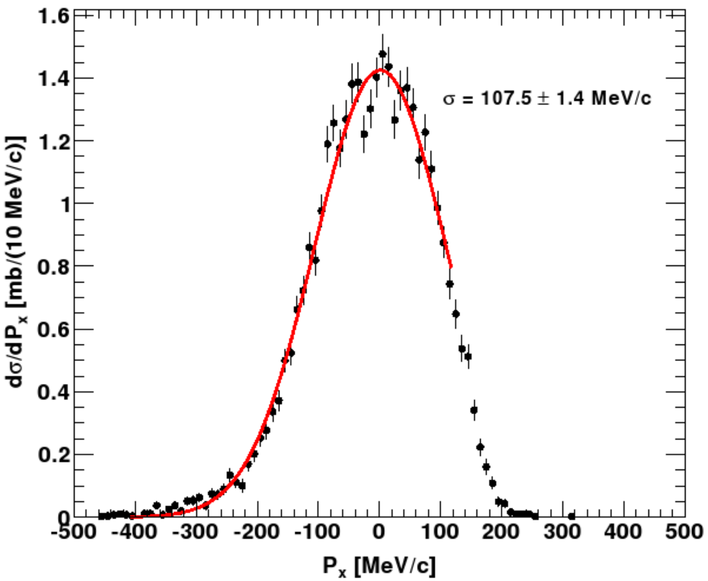
p-shell

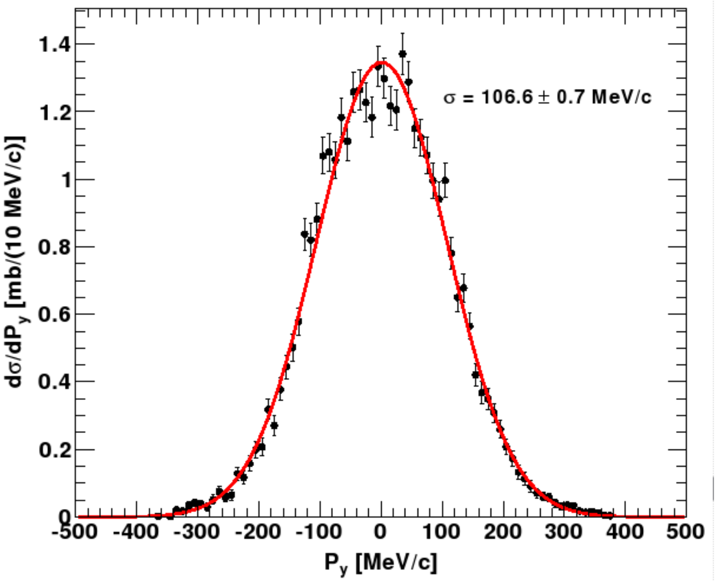
$^{12}C(p,2p)X$

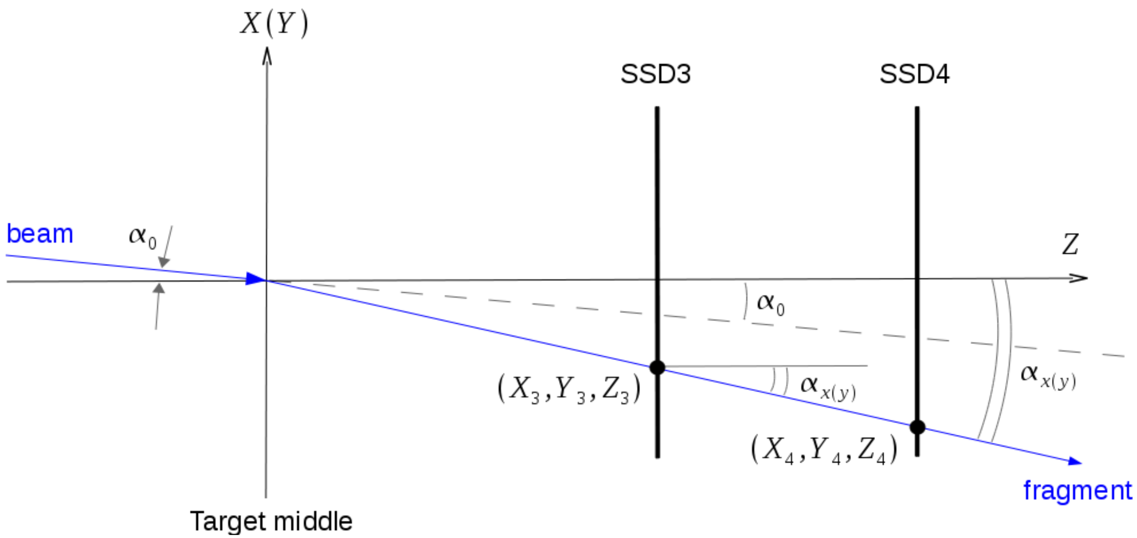


s-shell

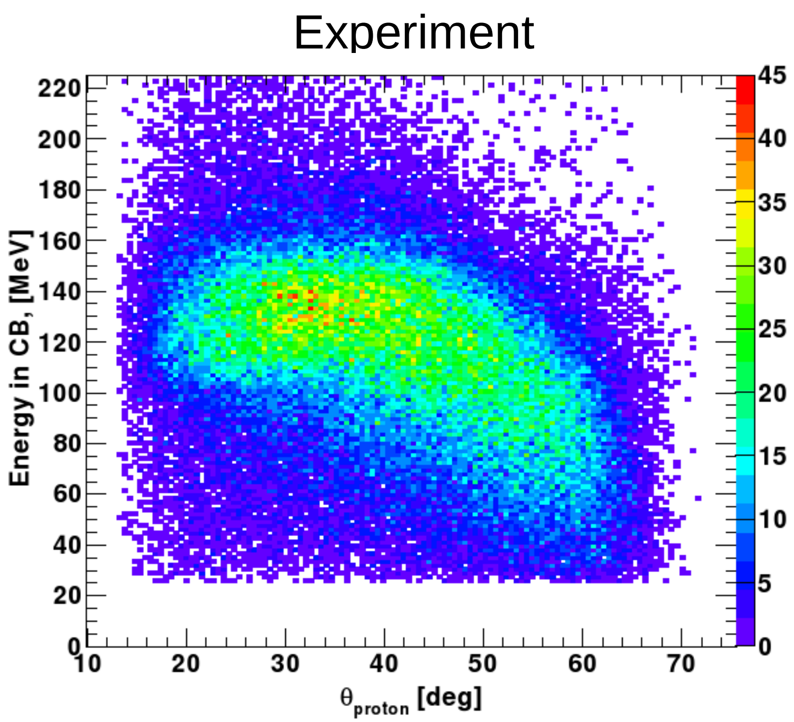
Recoil Momentum (p-shell knockout)

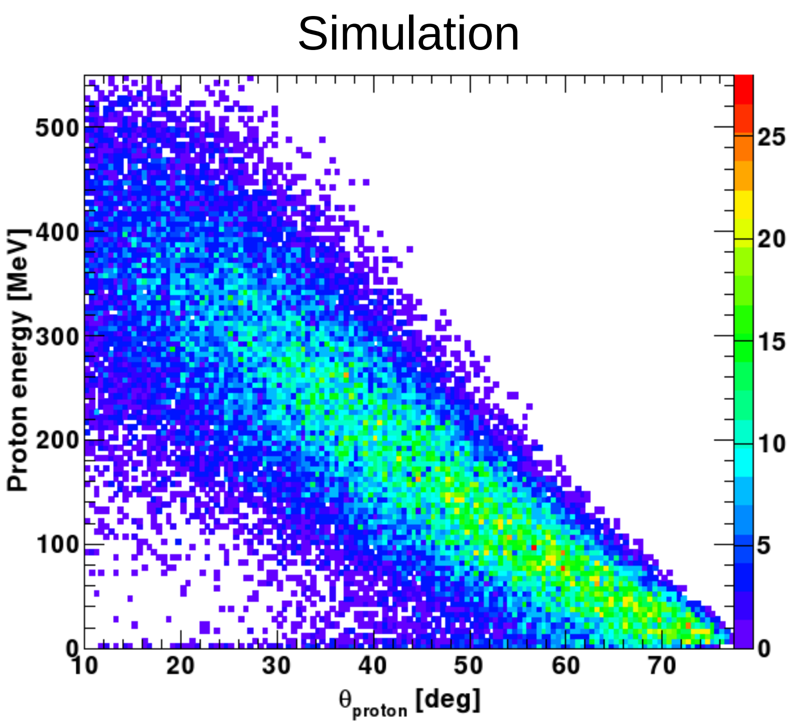






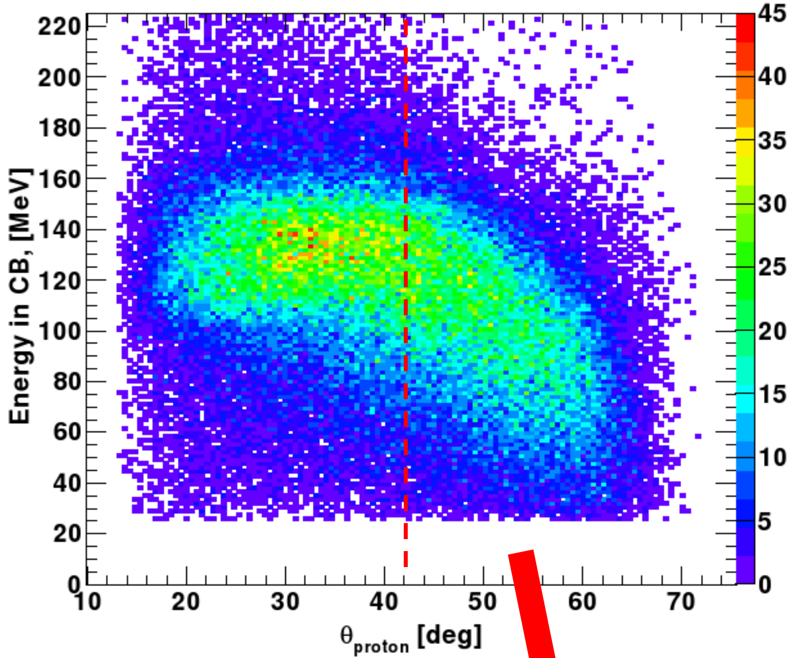
Energy Measurements of QFS protons



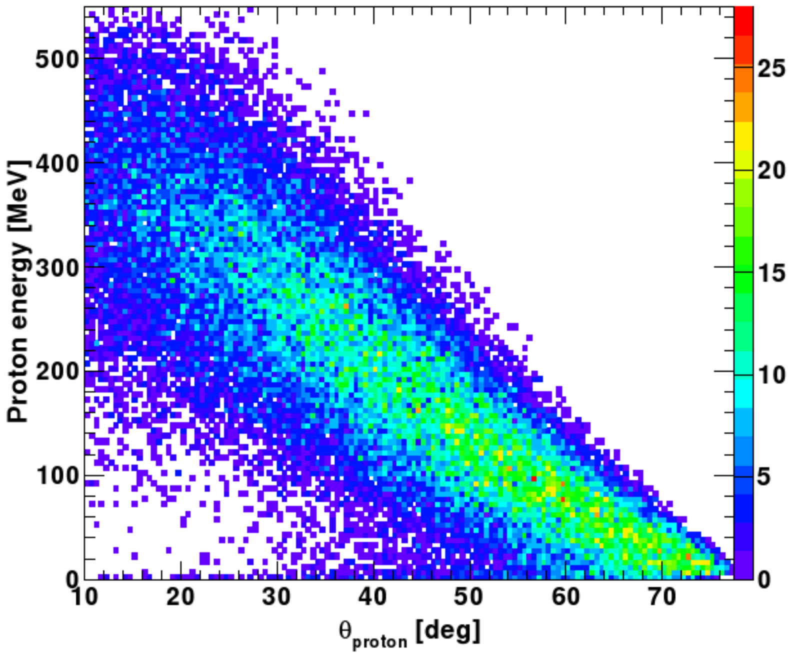


Energy Measurements of QFS protons

Experiment



Simulation

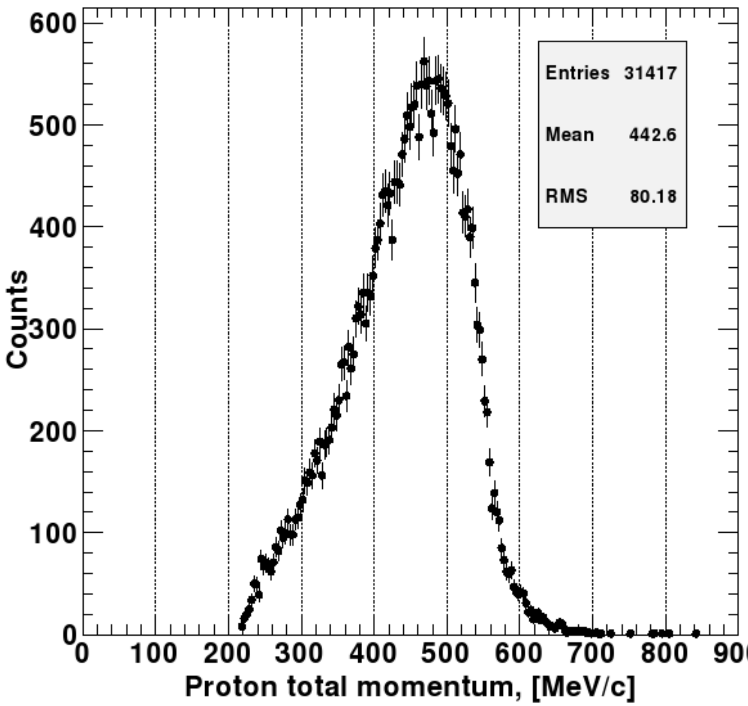


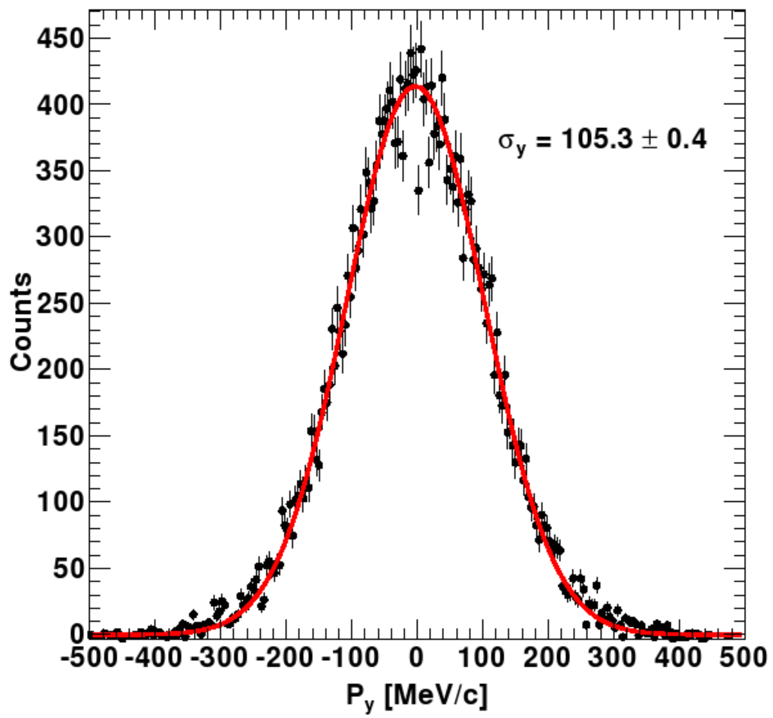
$$Q = \frac{1}{c}\sqrt{E_k(E_k + 2m_p c^2)}$$ → total momentum of a proton

$$P_{x,y} = Q_k \times sin\theta_k sin(\varphi_k - \varphi_i)$$ → transverse component of internal momentum

L. Chulkov et al. Nucl.Phys. A759, 43, (2005)

Internal Momentum Measurements via QFS protons





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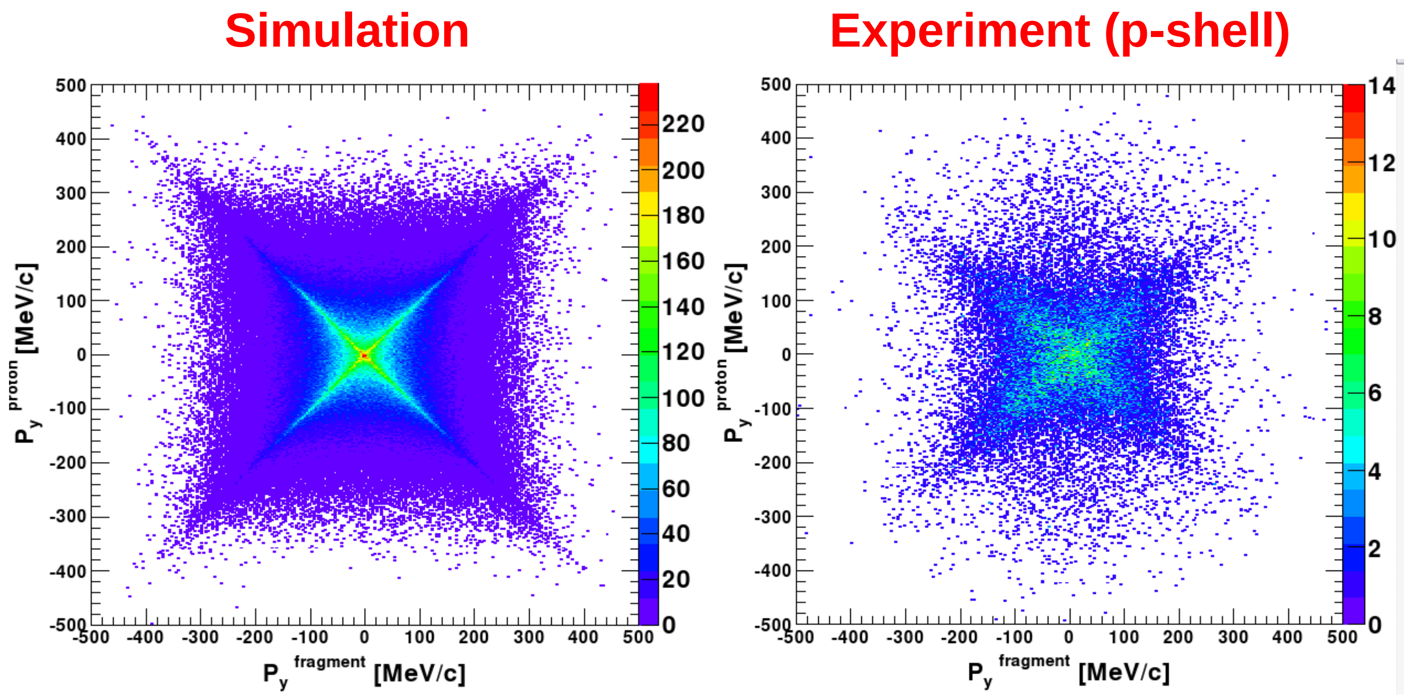
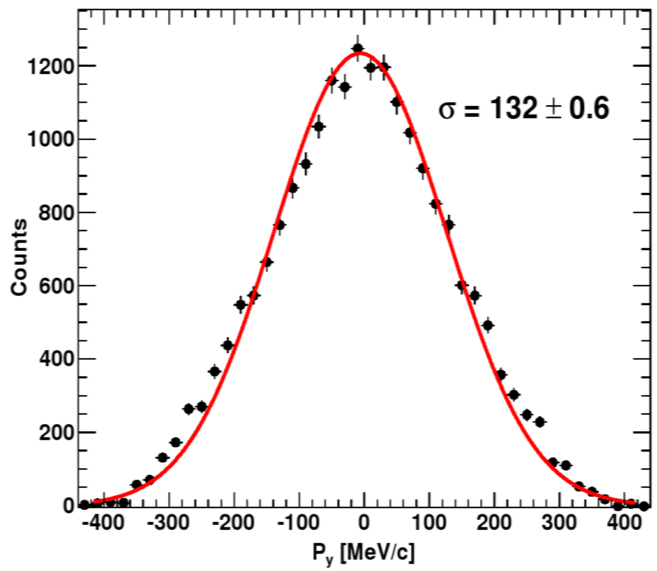
L. Chulkov et al. Nucl.Phys. A759, 43, (2005)





← Internal momentum distribution of protons in s-shell

26% increased comparing to p-shell knock-out

Reaction \ Target	CH_2	Carbon	Hydrogen
$^{12}\mathrm{C}(p,2p)X$	89.2 ± 2.2	23.6 ± 1.0	32.8 ± 1.2
$^{12}\mathrm{C}(p,2p)^{11}\mathrm{B}$	47.3 ± 1.6	11.1 ± 0.7	18.1 ± 0.9
p-removal	82.7 ± 7.7	45.9 ± 4.4	18.4 ± 2.7
pn-removal	48.1 ± 5.3	30.7 ± 2.3	8.7 ± 1.7
Inelastic breakup	2.64 ± 0.97	0.96 ± 0.65	0.84 ± 0.59

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16 ± 4 mb
integral (p,2p) c.s. for p-shell
Nuclear Physics 18 (1960) 46---64,

Reaction \ Target	CH_2	Carbon	Hydrogen
$^{12}\mathrm{C}(p,2p)X$	89.2 ± 2.2	23.6 ± 1.0	32.8 ± 1.2
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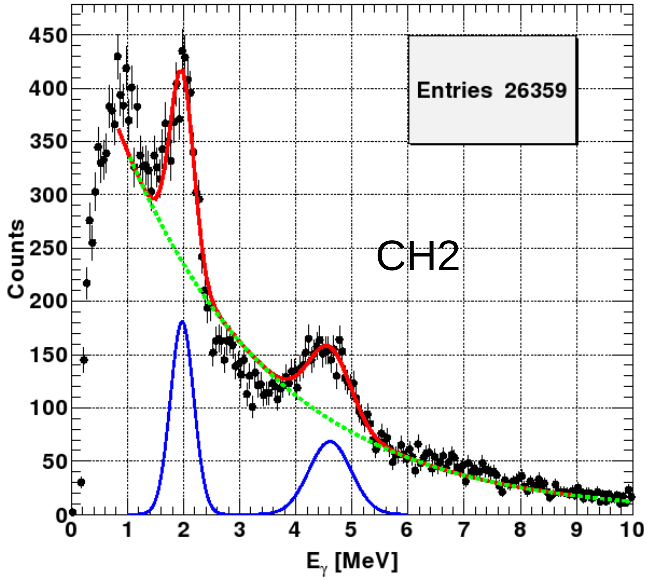
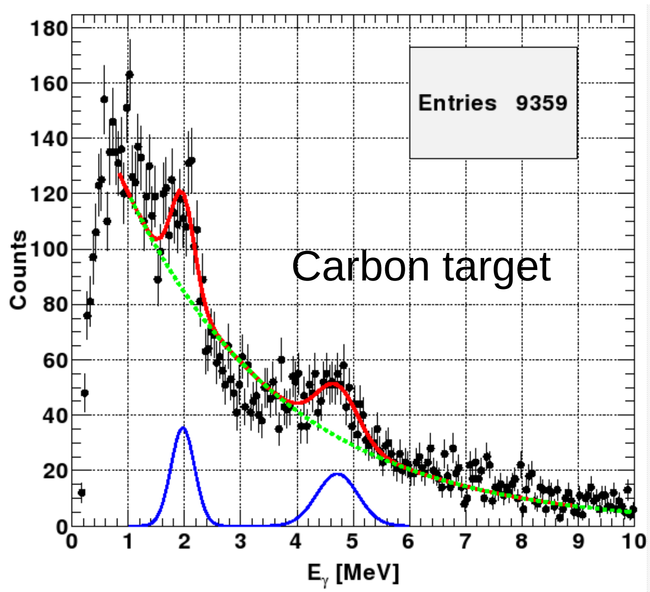
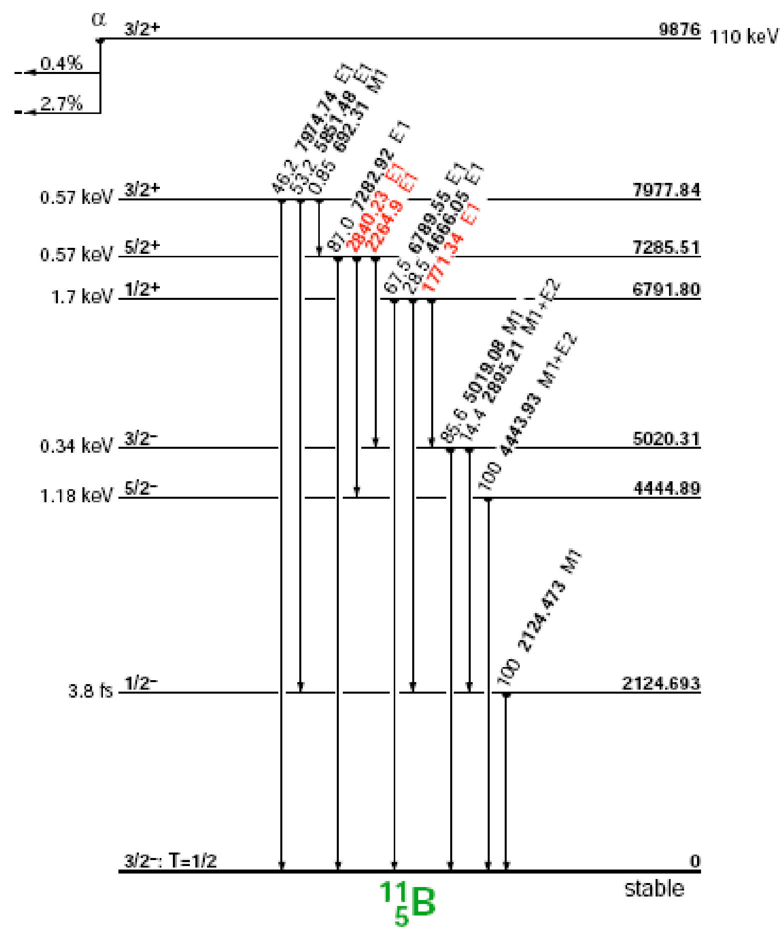
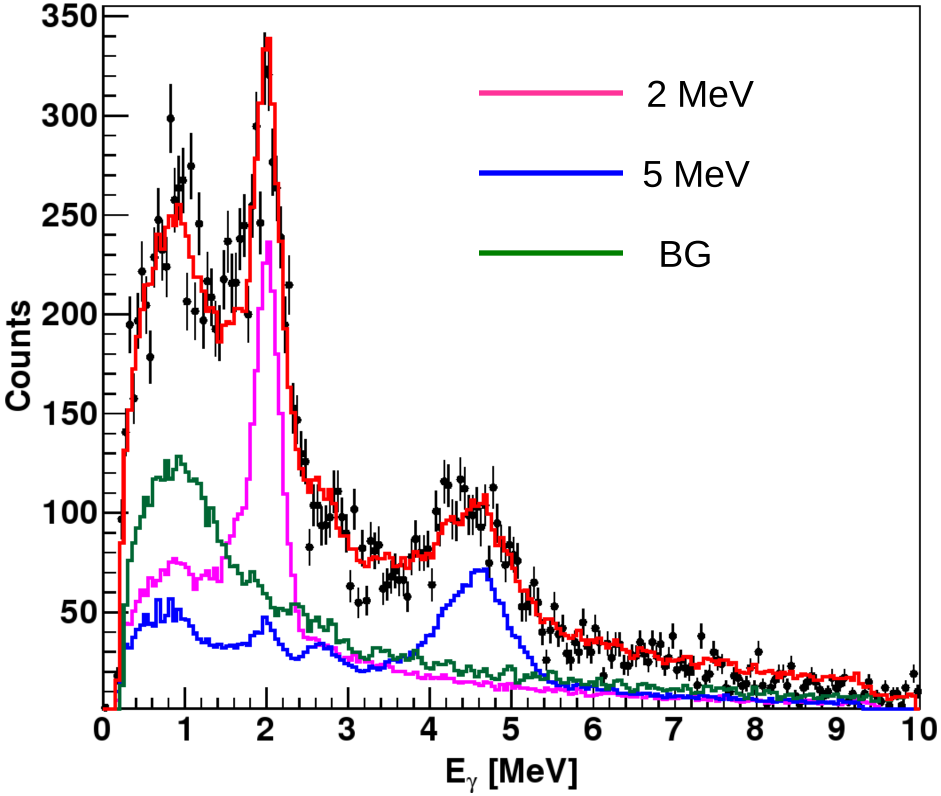
14.7 mb (45%) to unbound states (s-shell)

Doppler corrected gamma-spectrum in coincidence with $^{12}C(p,2p)^{11}B$ reaction









BG subtracted gamma-spectrum:

2 MeV: 17% (3.1 ± 0.2 mb)

5 MeV: 12% (2.2 ± 0.1 mb)

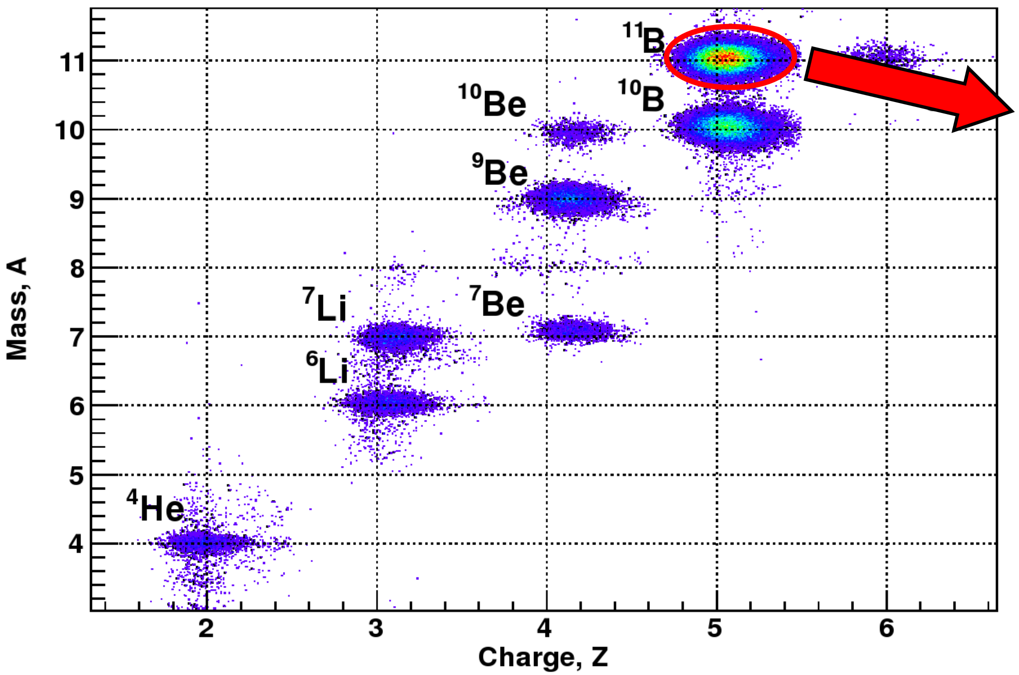
G.S : 71% (12.9 ± 0.8 mb)

Comparison with relative spectroscopic factors

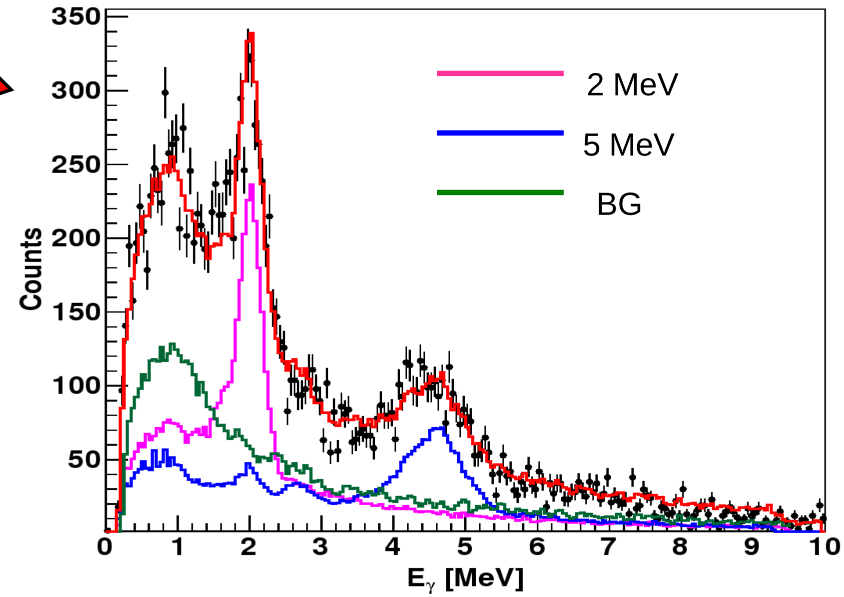
	present exp.	(p,2p)[2] @ 100MeV	(e,e'p)[1]	(d,^{3}He)[1]	Cohen-Kurath[1]
G.S	0.71	0.76	0.79	0.75	0.71
2 MeV	0.17	0.12	0.12	0.17	0.19
5 MeV	0.12	0.12	0.09	0.08	0.10

[1] *Aust. J. Phys.*, 1979, 32, 323-34
[2] Nuclear Physics A480 (1988) 547-572

Reconstruction of excitation energy in ^{11}B



Gamma spectrometry

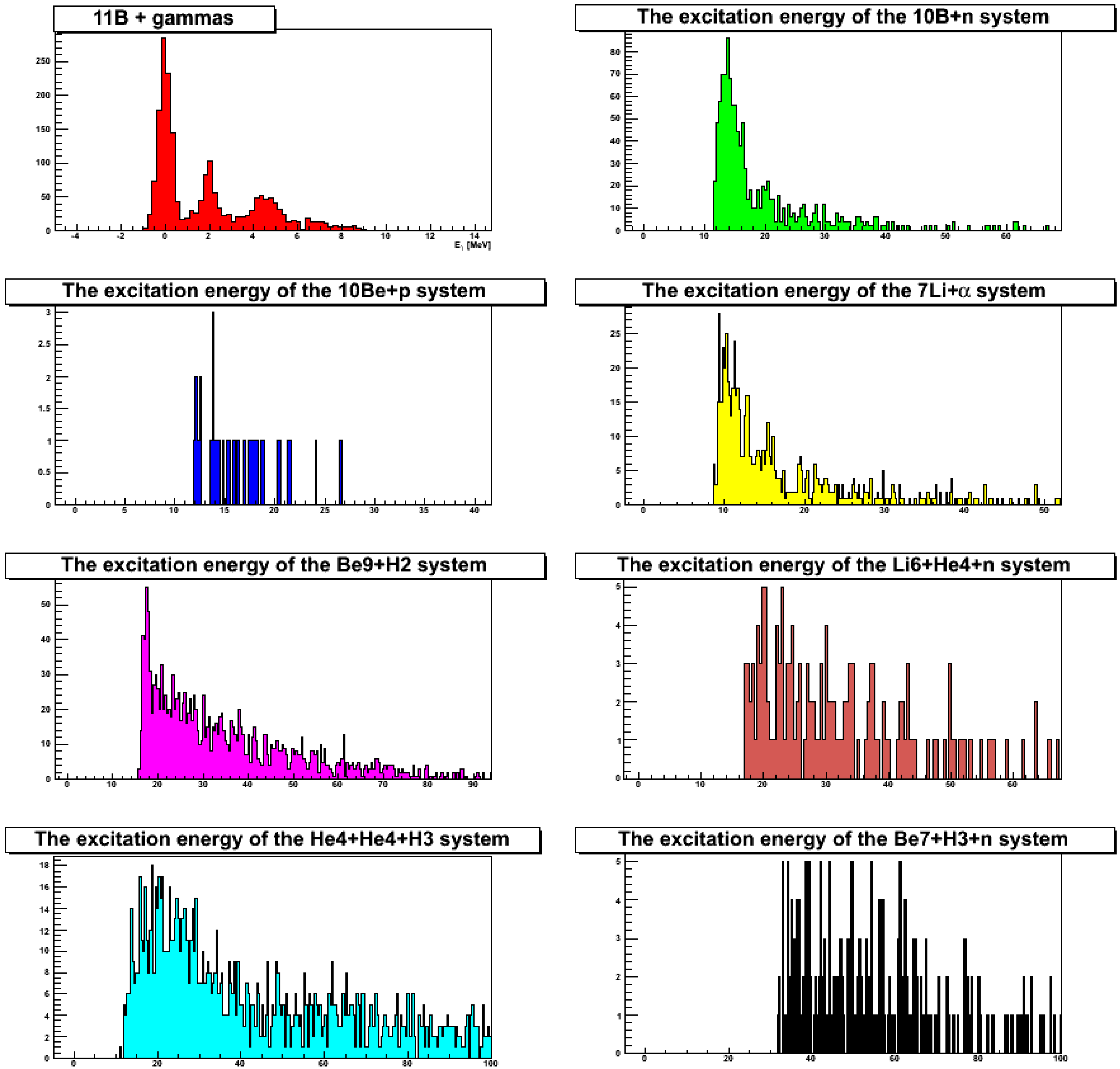


Invariant mass method for breakup channels
(s-shell knock-out)

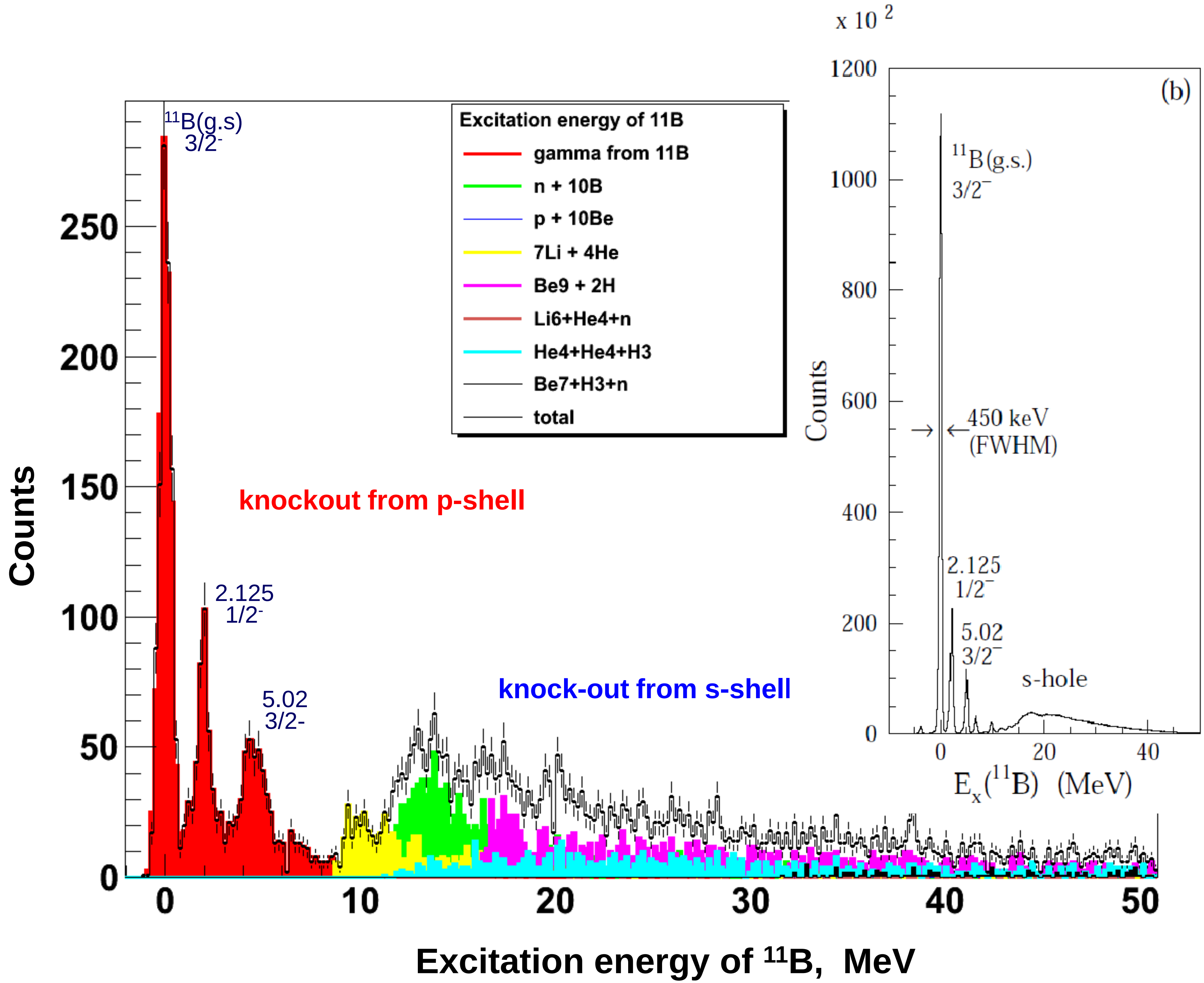
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j cos\vartheta_{ij})} + E_\gamma - m_{proj}$$

$^{11}B^* \rightarrow$

- $^{10}B + n$
- $^{7}Li + {}^{4}He$
- $^{10}Be + p$
- $^{9}Be + {}^{2}H$
- $^{6}Li + {}^{4}He + n$
- $^{7}Be + {}^{3}H + n$
- ....

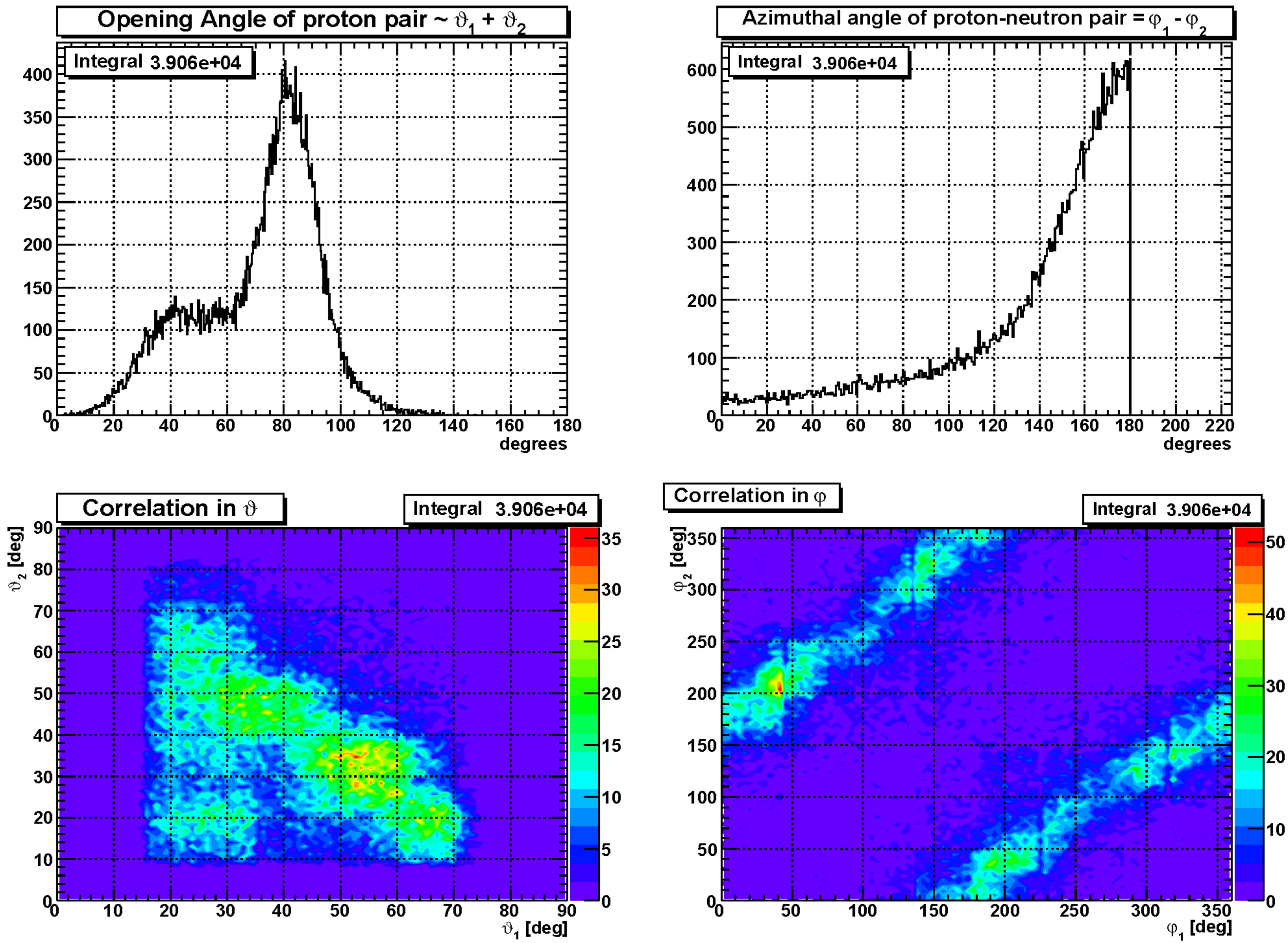


11B + gammas
The excitation energy of the 10B+n system
The excitation energy of the 10Be+p system
The excitation energy of the 7Li+α system
The excitation energy of the Be9+H2 system
The excitation energy of the Li6+He4+n system
The excitation energy of the He4+He4+H3 system
The excitation energy of the Be7+H3+n system

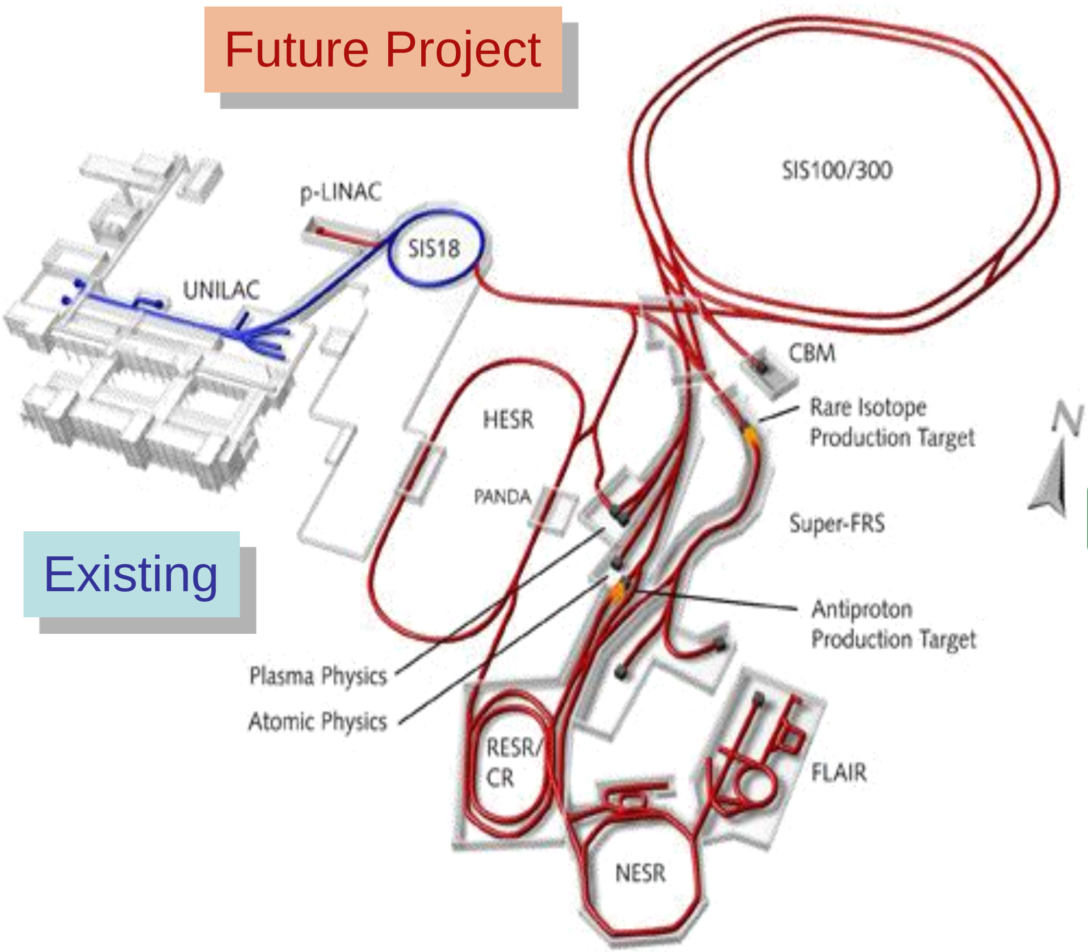


Excitation energy of 11B
gamma from 11B
n + 10B
p + 10Be
7Li + 4He
Be9 + 2H
Li6+He4+n
He4+He4+H3
Be7+H3+n
total
11B(g.s) 3/2-
2.125 1/2-
5.02 3/2-
knockout from p-shell
knock-out from s-shell
Counts
Excitation energy of 11B, MeV
x 10 2
(b)
11B(g.s.) 3/2−
450 keV (FWHM)
2.125 1/2−
5.02 3/2−
s-hole
Counts
Ex(11B) (MeV)

Angular Distributions of p-n pair from $^{12}C(p,pn)^{11}C$ Reaction



FAIR: Facility for Antiproton and Ion Research



Primary Beams

- 10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- 2(4)x10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- up to 90 GeV protons

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 - 30 GeV

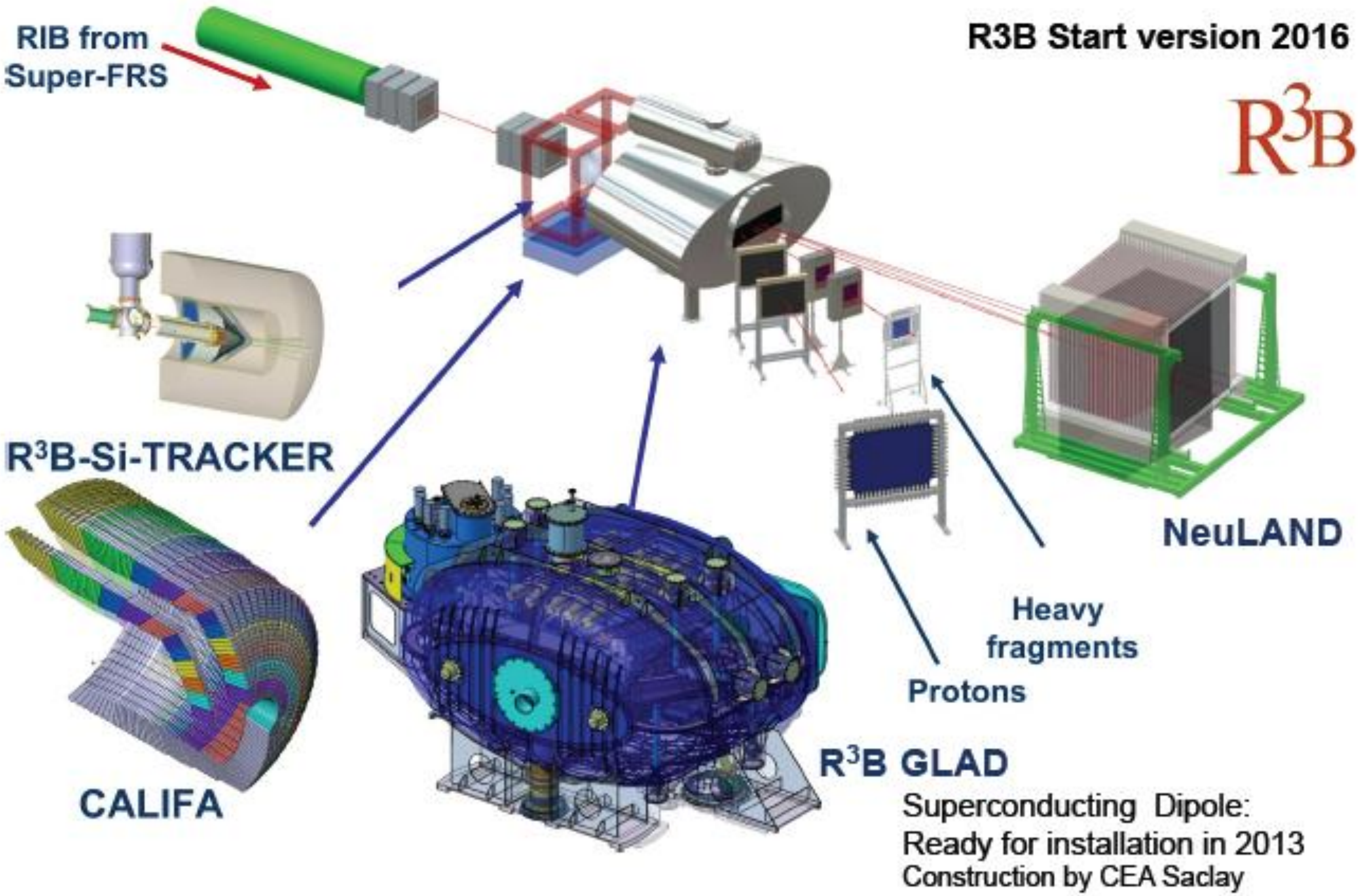
Storage and Cooler Rings

- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

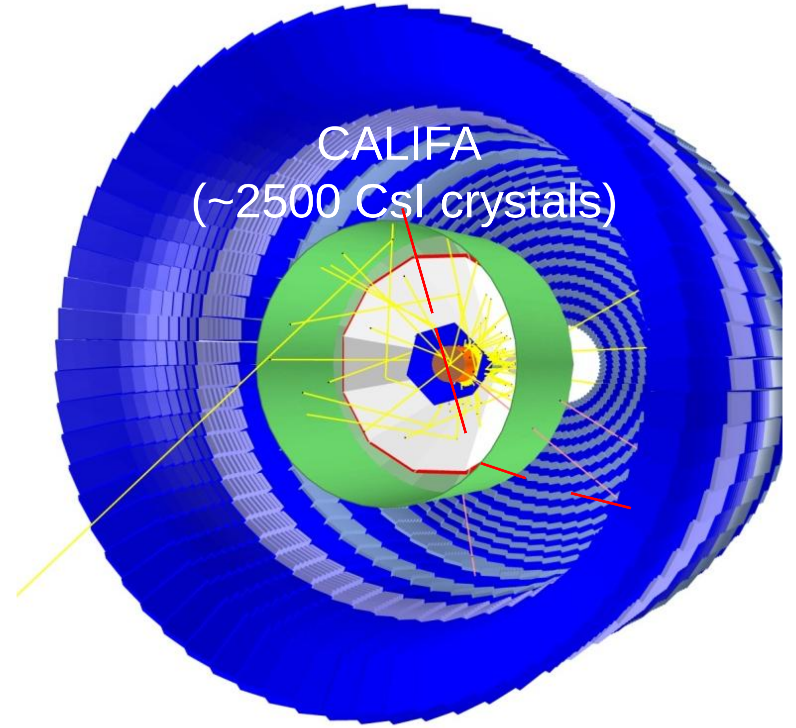
- Cooled beams
- Rapidly cycling superconducting magnets

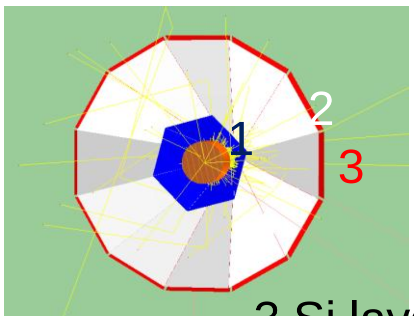
Reactions with Relativistic Radioactive Beams

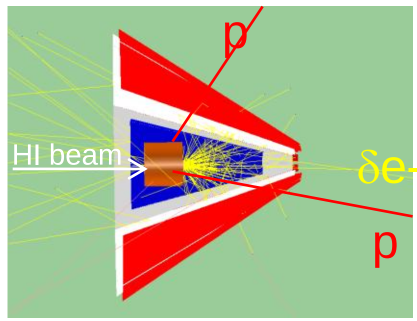


Si Tracker for R3B

- **Target recoil detector for typical (p,2p) reactions:**
  - **Si tracker (UK)**
  - **Calorimeter CALIFA (Spain led collaboration)**
  - **LH2 target (France and UK)**





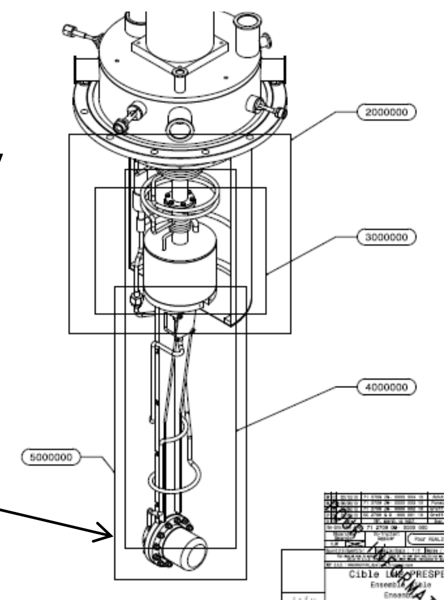


3 Si layers

- **Designed to detect target recoil particles from reactions of RIBs with LH2 target**
  - **e.g. protons with energies from 50 – 500 MeV**

<u>LH2:</u>
∅ 70 mm
Thickness < 61mm

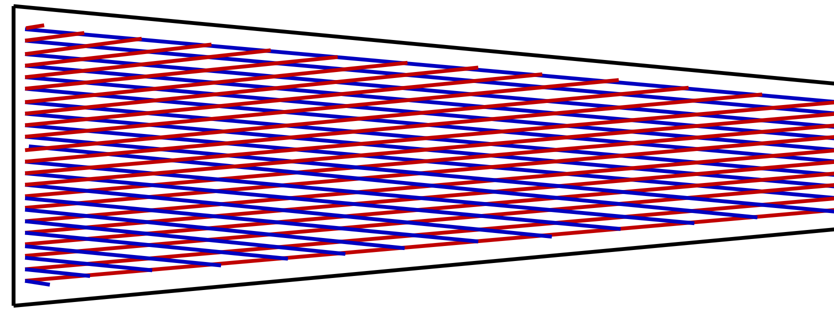
<u>Mylar envelope:</u>
150 -250 um



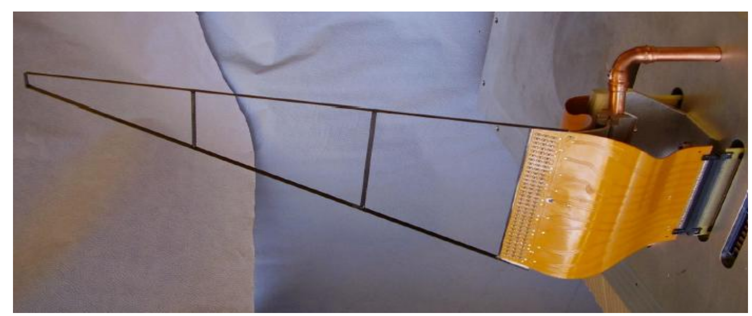
Si Tracker for R3B

- **Provide particle tracking and identification**
- **Prototype build with double sided stereo angle Si micro strip detector.**
- **50 um pitch strips**
- **Total channels for complete array: ~120k channels (using Si micro-strip)**
- **ASIC readout (912 ASICs, with 128 channels each)**
- **inner layer**
  - **reduce material as much as possible, thickness □ 100um.**
  - **Evaluating both MAPS and Si micro-strip options**
- **Two outer layers:**
  - **300um thick**
- **All layers: ~100 um position resolution**

Blue P side strips
Red N side strips
(Representation only)



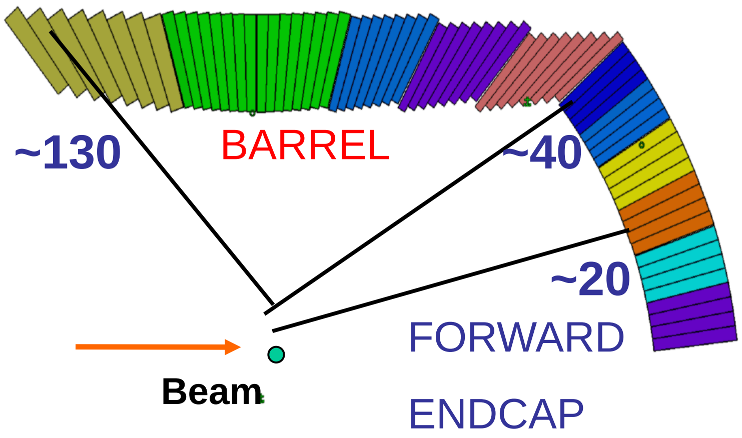
Each silicon detector is double sided with P and N side strips forming a STEREO angle detector arrangement



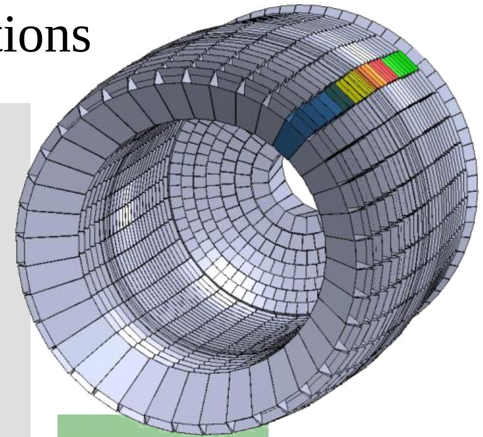
Ladder on which Si detectors and ASICs will be mounted

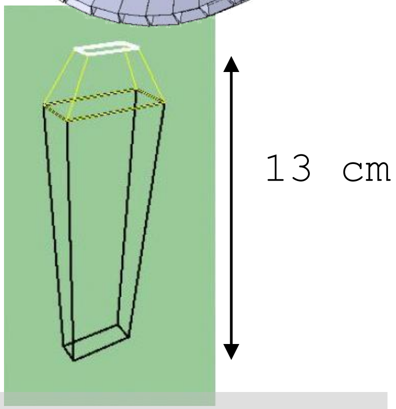
Calorimeter - CALIFA

General design of the detector based on kinematical considerations



"Egg" shape
Highly segmented
Thick detection volume
Scintillation based
performant photo-sensors



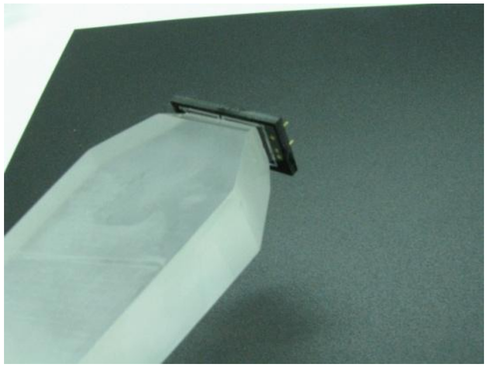


Real shape, 1MeV γ

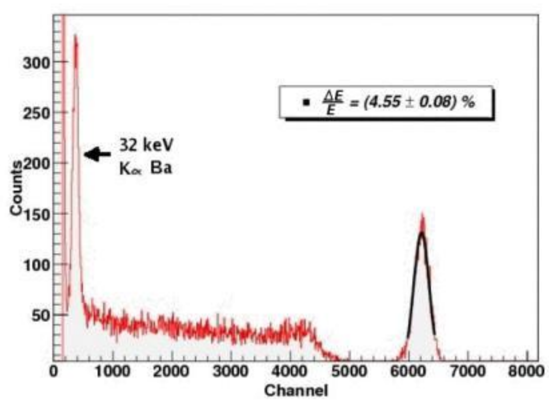
→ $\Delta E/E \sim 5$ %

Crystal and photosensors

Barrel →CsI+APD

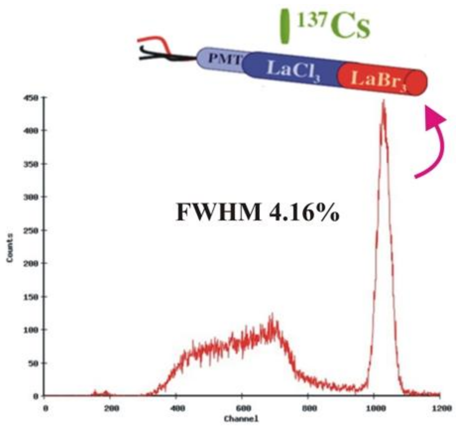


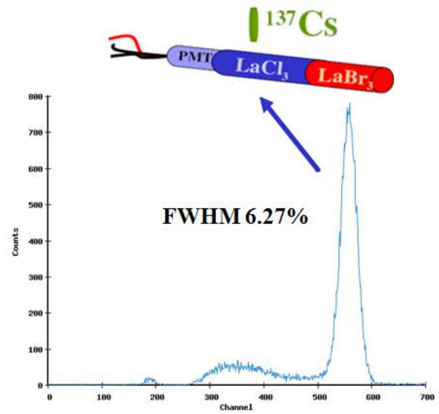
1cm^3 and 662 keV γ



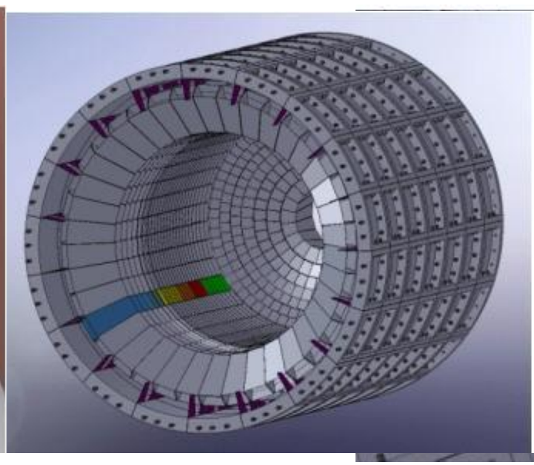
Calorimeter - CALIFA

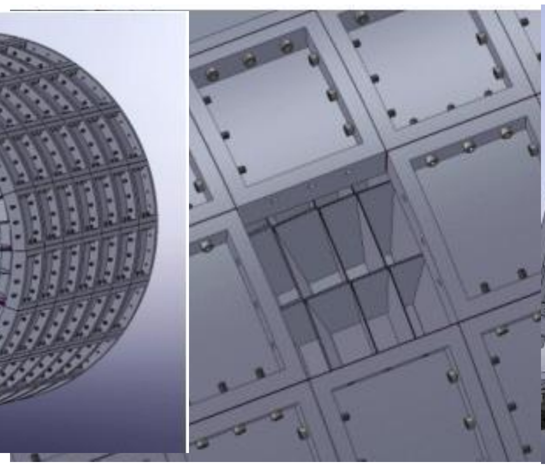
Forward Endcap → Phoswich solution is being investigated

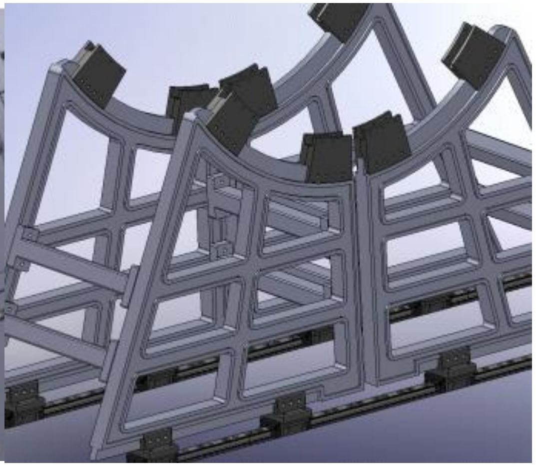




Engineering design and Mechanical structure → based on carbon fiber







Target Recoil Detector for High-Momentum Transfer Region ?

- If we use full RIB energy available at FAIR (1-1.5 AGeV), E_p < 1 GeV
- E-dE techniques alone will not work (punchthrough, secondary reaction losses in scintillator, etc.
- Possible concept based on tracking in magnetic field

HERMES recoil detector
- 1T solenoid field

<u>Silicon & Fiber Tracker:</u>

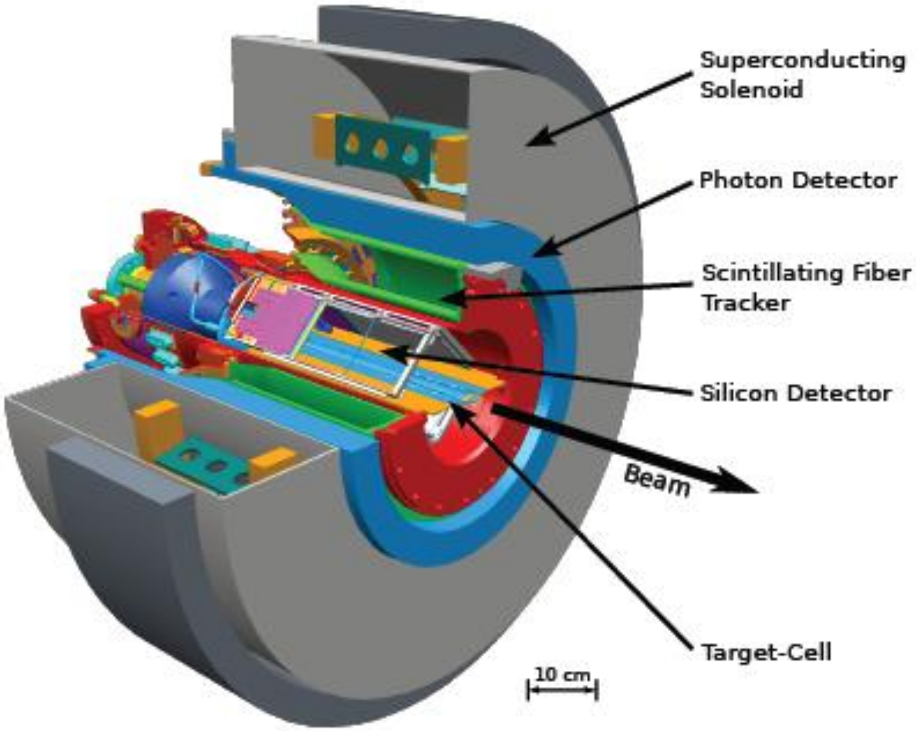
$p_{\mathrm{p}} \in [135, 1200]$ MeV/c

p/π PID for $p < 650$ MeV/c

<u>Photon Detector:</u>

p/π PID for $p > 600$ MeV/c

π^0 background supression



Summary

• QFS a powerful and unique tool to explore correlations and in-medium nucleon properties in asymmetric nuclei
• Both valence and deeply bound nucleons can be studied
• Strong synergy with studies of nuclear matter and neutron stars

• R3B at GSI/FAIR is ideally suited for such studies with beam energies up to 1000 AMeV +
• First experiments with simple target recoil detector in Cave C:
  • Ongoing analysis of ^{17}Ne and ^{12}C (p,2p) at 400 AMeV
  • New experiment approved to study complete O isotopic chain in 2010

• New target recoil detector being designed/constructed to significantly enhance capabilities for QFS studies at R3B
• Development of programme to study QFS at high momentum transfer at FAIR

• NOTE: (p,2p) measurements with multi (1-30) GeV protons beams on symmetric nuclei will also be possible at FAIR, e.g. PANDA, CBM