# Physics programme at a high-resolution spectrometer for relativistic radioactive beams at FAIR

## The R3B High-Resolution Spectrometer

*Thomas Aumann*

TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

HIC for FAIR
Helmholtz International Center

Bundesministerium für Bildung und Forschung

GSI

NAVI
Nuclear Astrophysics Virtual Institute

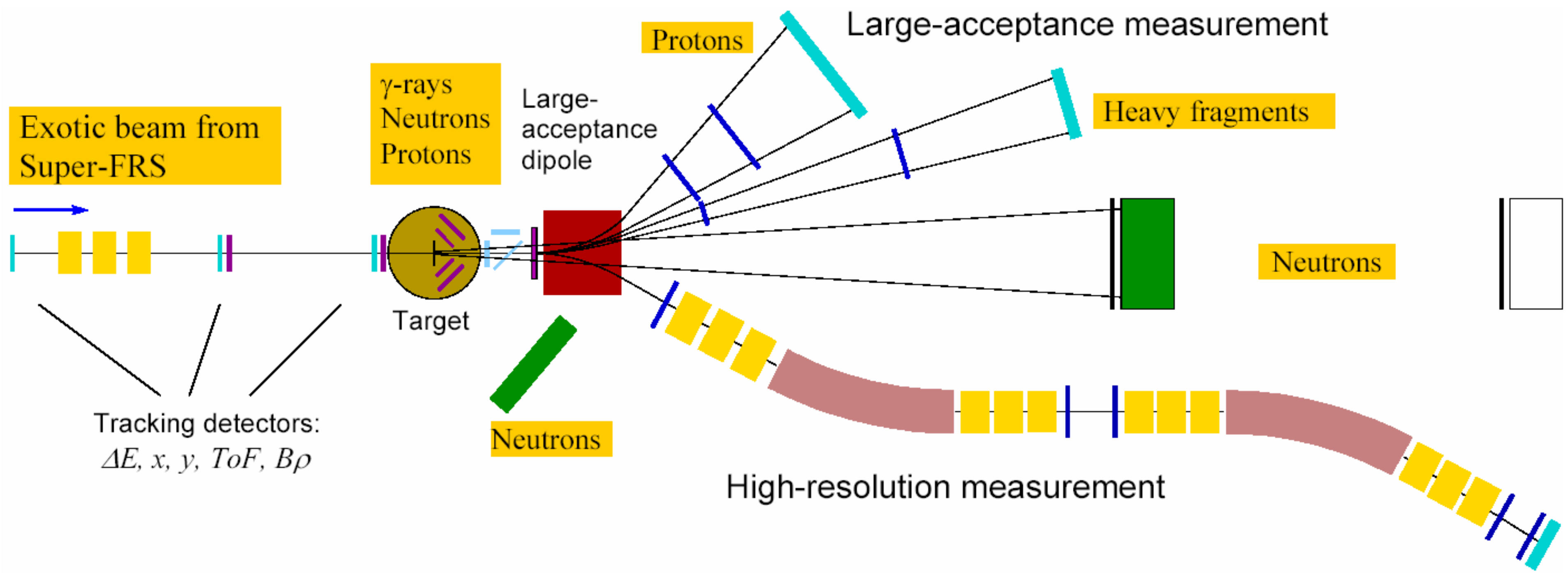
ENSAR

EMMI

**NuSTAR – meeting - February 27th 2013**

- The R3B concept
- Need for large-acceptance and high-resolution mode
- Example: Quasi-free knockout reactions
- Conclusion

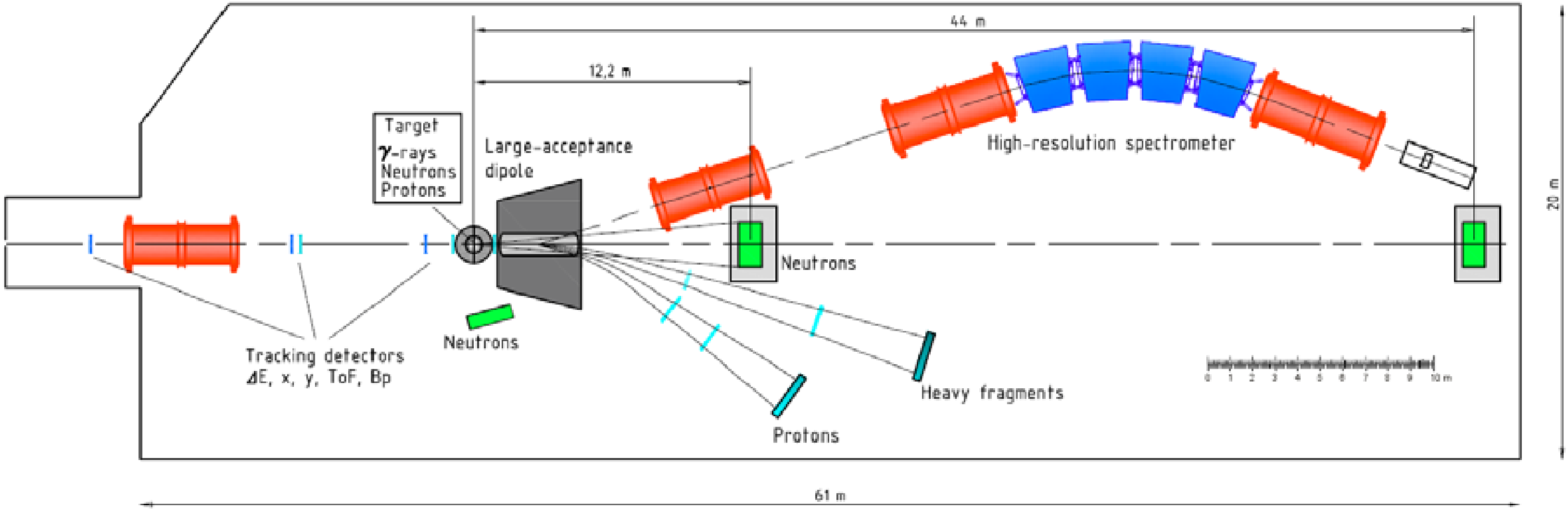
# The R3B experimental concept

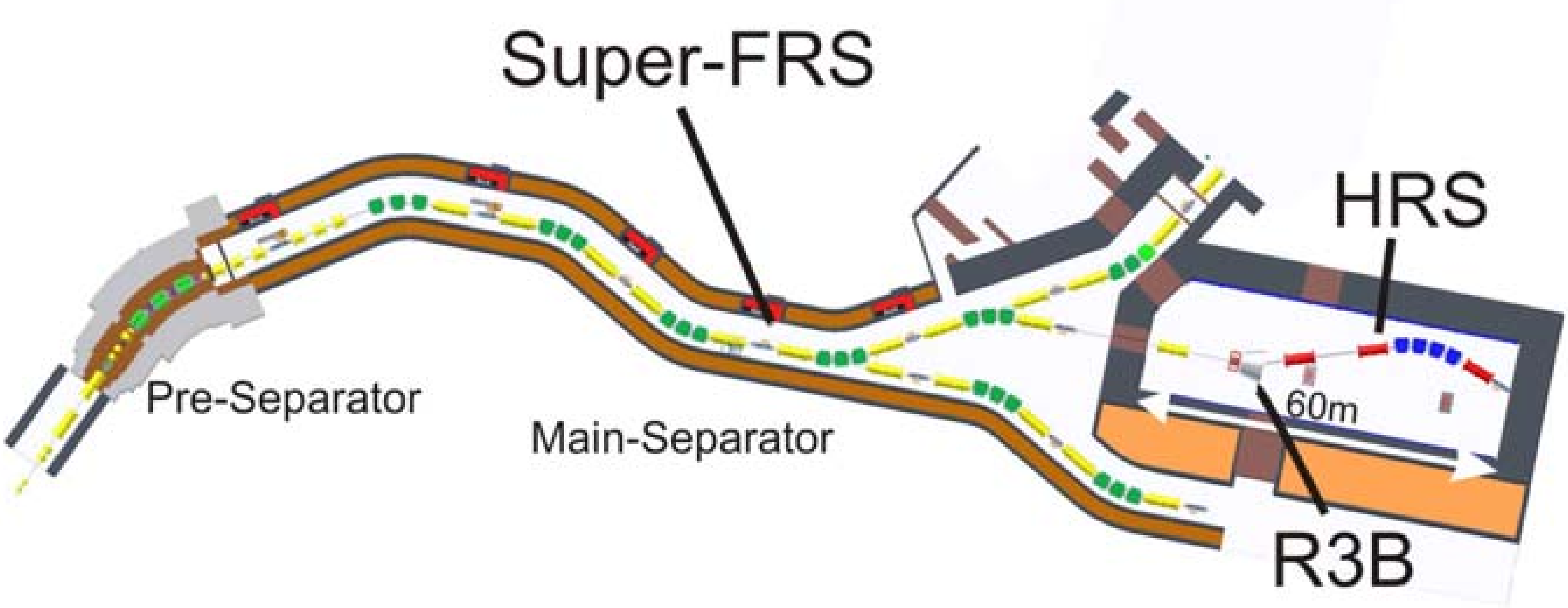



- Large-acceptance mode: $\Delta B\rho/B\rho \sim 10^{-3}$, -5 to 41 degree, ±80 mrad vert. acceptance
- High-resolution mode: $\Delta B\rho/B\rho \sim 10^{-4}$, ±2.5% mom. acc., ±80 mrad vert. at 0 degree

R3B Letter of Intent (April 2004)
R3B Technical Proposal (Dec 2005)

# Possible layout of R3B with high-resolution spectrometer



# Summary of R3B physics programme

*Table 1. Reaction types with high-energy beams measurable with $R^3B$ and corresponding achievable information*

| *Reaction type* | *Physics goals* |
|---|---|
| Knockout | Shell structure, valence-nucleon wave function, many-particle decay channels unbound states, nuclear resonances beyond the drip lines |
| Quasi-free scattering | Single-particle spectral functions, shell-occupation probabilities, nucleon-nucleon correlations, cluster structures |
| Total-absorption measurements | Nuclear matter radii, halo and skin structures |
| Elastic p scattering | Nuclear matter densities, halo and skin structures |
| Heavy-ion induced electromagnetic excitation | Low-lying transition strength, single-particle structure, astrophysical S factor, soft coherent modes, low-lying resonances in the continuum, giant dipole (quadrupole) strength, polarizability, neutron skin, symmetry energy |
| Charge-exchange reactions | Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness |
| Fission | Shell structure, dynamical properties |
| Spallation | Reaction mechanism, astrophysics, applications: nuclear-waste transmutation, neutron spallation sources |
| Projectile fragmentation and multifragmentation | Equation-of-state, thermal instabilities, structural phenomena in excited nuclei, $\gamma$-spectroscopy of exotic nuclei |

R3B Technical Proposal, December 2005

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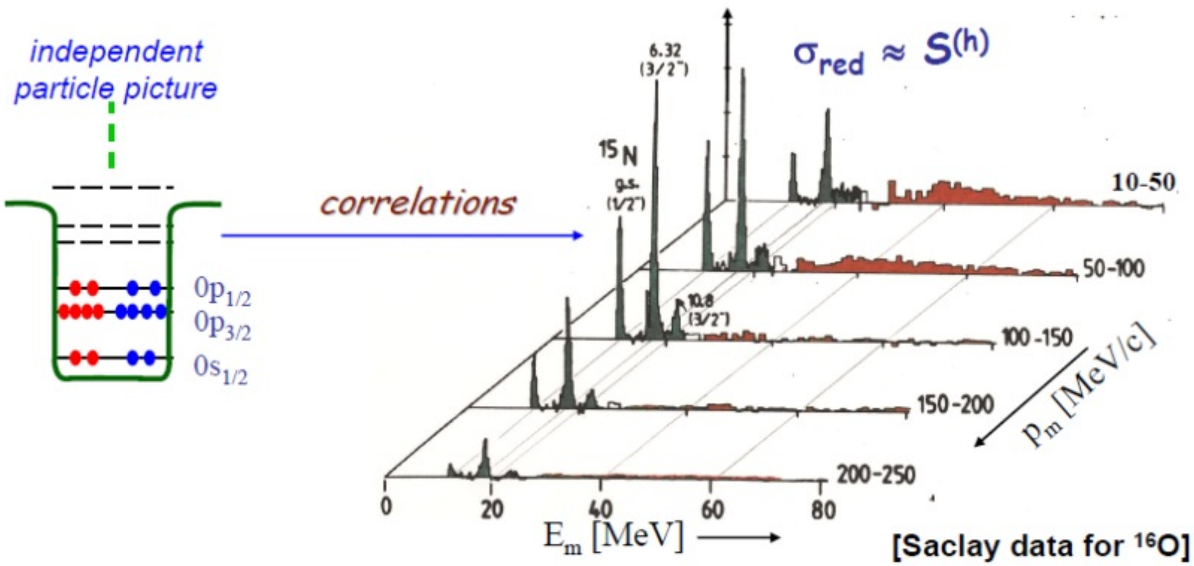
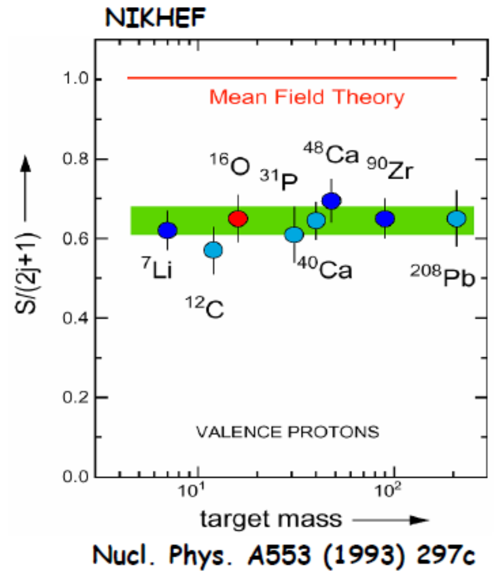
R3B Technical Proposal, December 2005

# Single-particle structure and correlations




Deviation from the independent-particle picture:

Correlations: Configuration mixing,

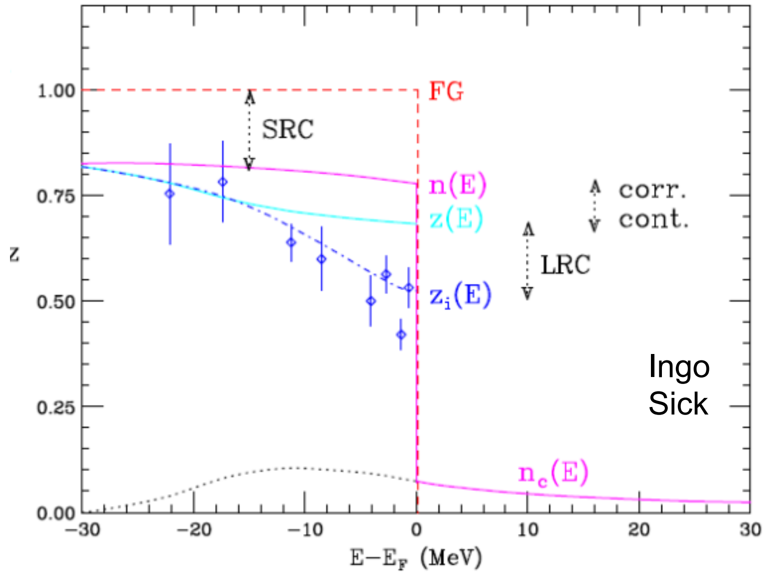
Coupling to collective phonons

Short-range and tensor correlations

→ high momenta

→ reduced single-particle strength

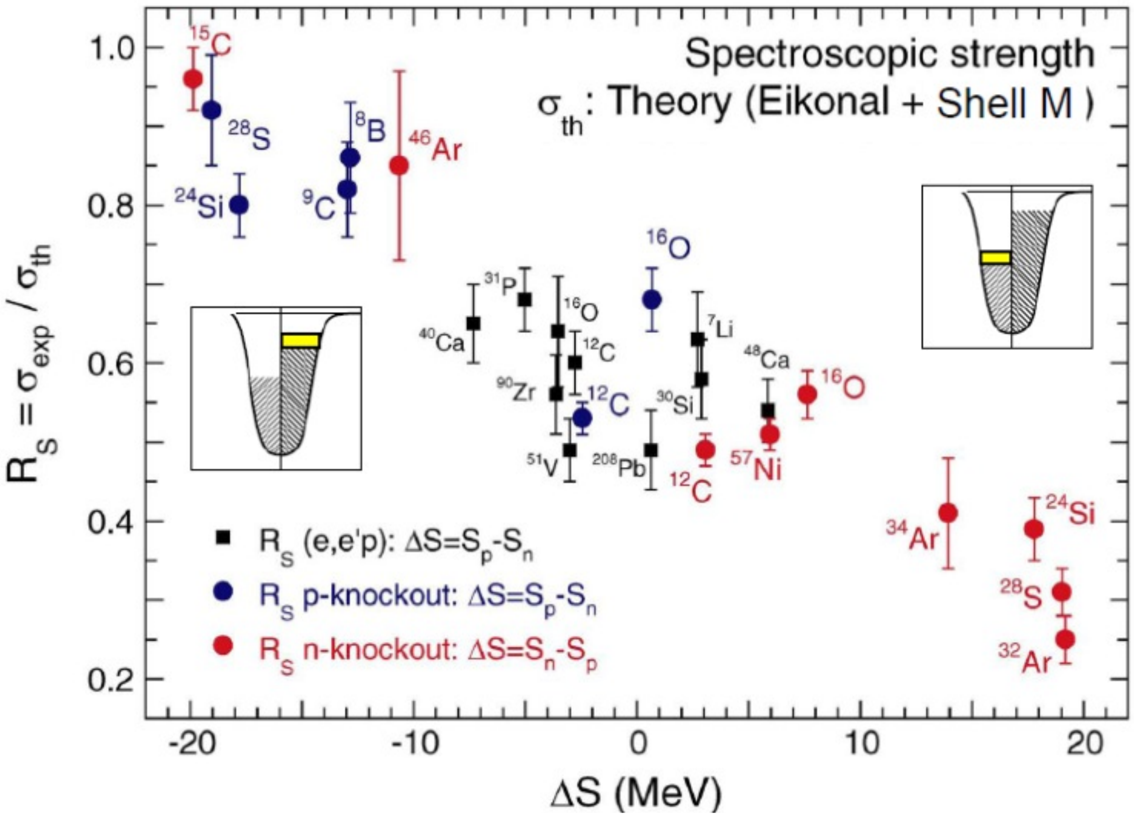
(occupations, spectroscopic factors)



# Single-particle cross sections
# Quenching for neutron-proton asymmetric nuclei

weakly bound nucleons

strongly bound nucleons



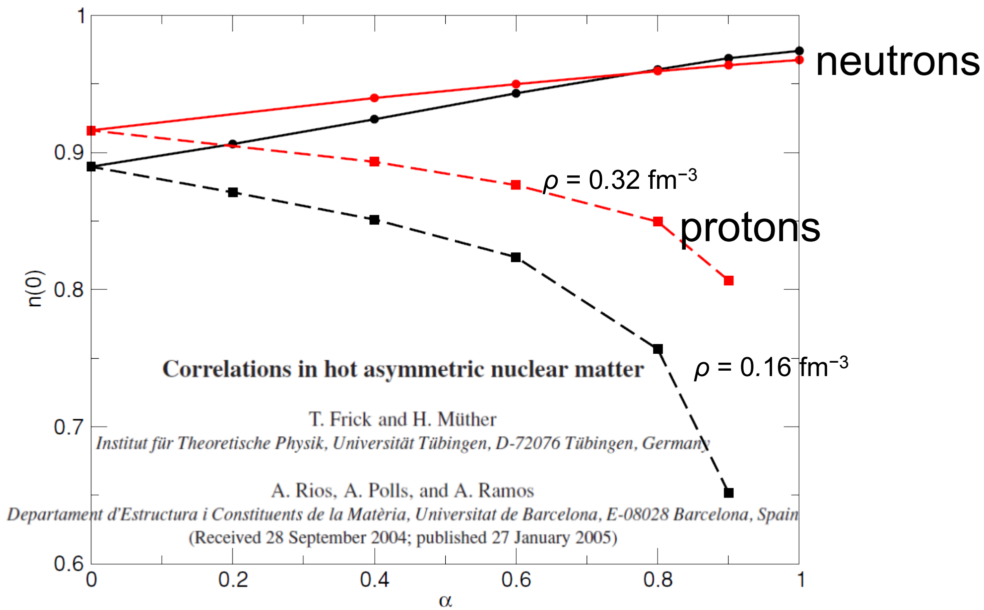

?

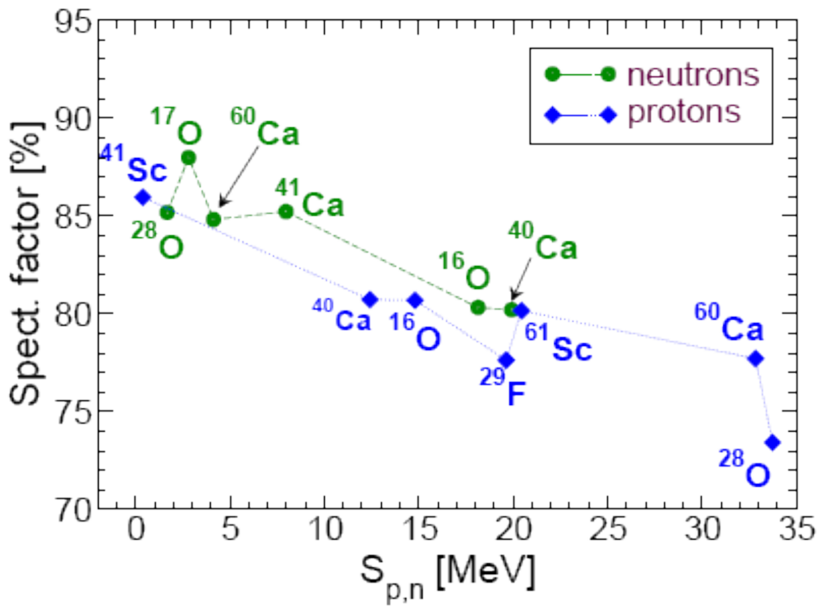
Origin unclear

?

Figure from Alexandra Gade, Phys. Rev. C 77, 044306 (2008)

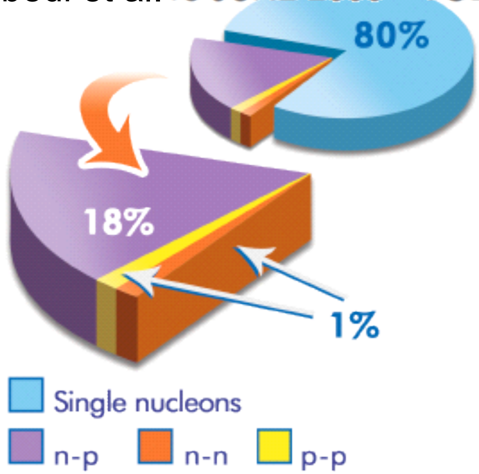
# Correlations in asymmetric nuclei and nuclear matter

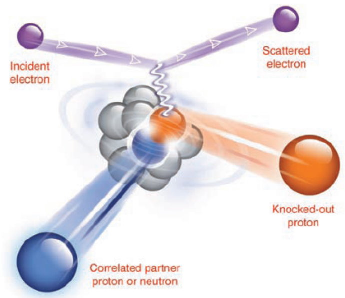



**Probing Cold Dense Nuclear Matter**

Subedi et al. 13 JUNE 2008 VOL 320 SCIENCE




Electron-induced knockout (JLab)

SPECTROSCOPIC FACTORS IN $^{16}$O AND NUCLEON ASYMMETRY

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


C. Barbieri

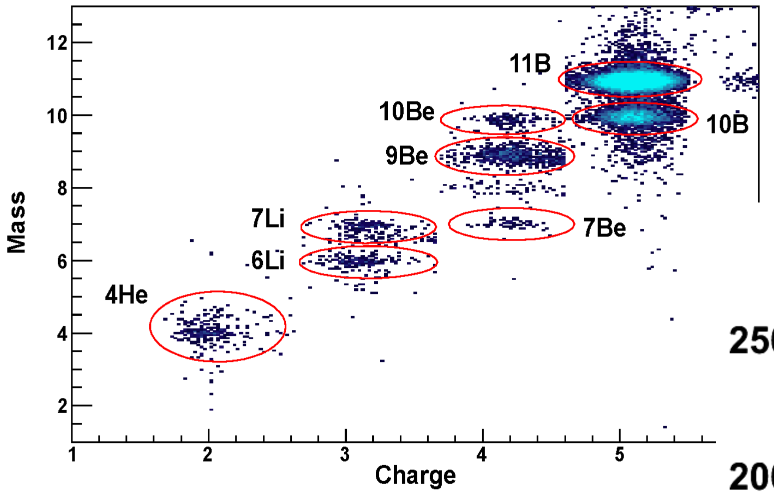
*Theoretical Nuclear Physics Laboratory, RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198 Japan*

W. H. Dickhoff

*Department of Physics, Washington University, St.Louis, Missouri 63130, USA*

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

Fragments produced in $^{12}C(p,2p)$



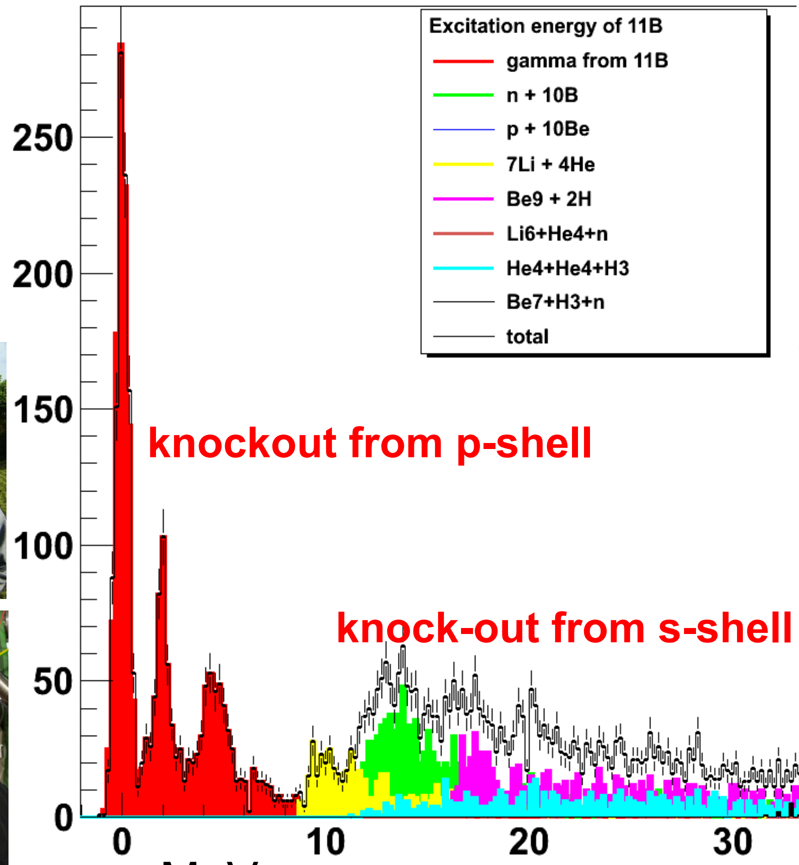

Jon Taylor, PhD thesis,

Univ. of Liverpool

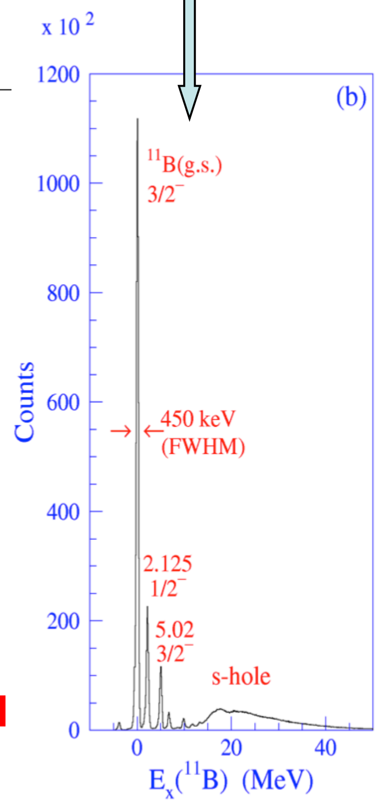
Valeri Panin, PhD thesis,

TU Darmstadt

Reconstructed excitation energy of $^{11}B$



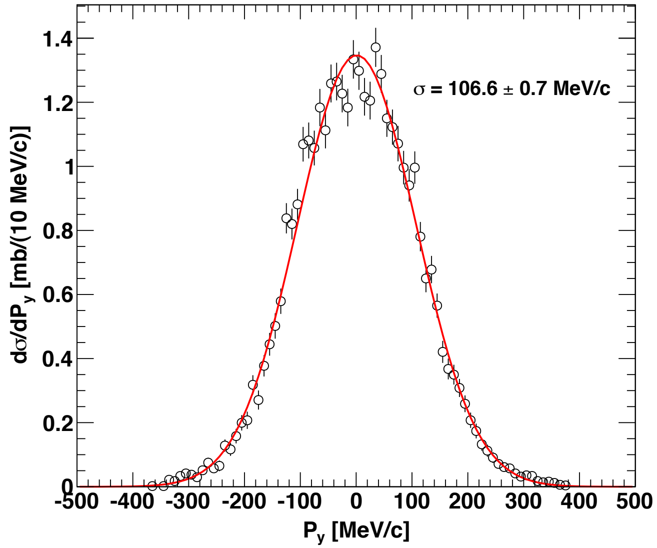

M. Yosoi, PhD Thesis, 2003, Kyoto University



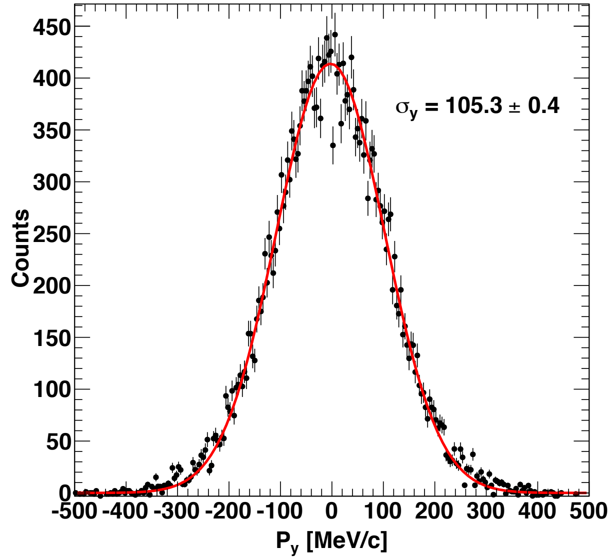

R3B preliminary data 2011, unpublished

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

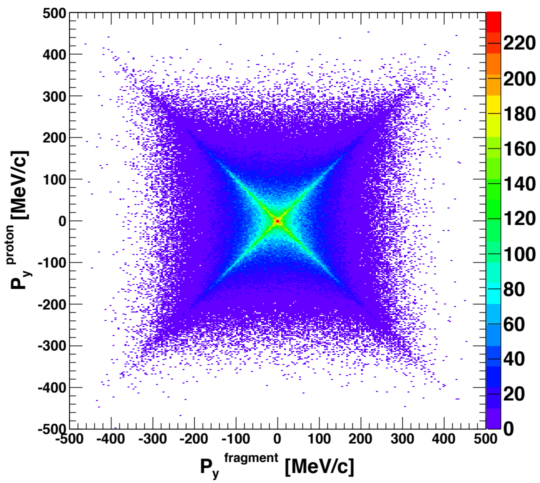
**Fragment recoil momentum**

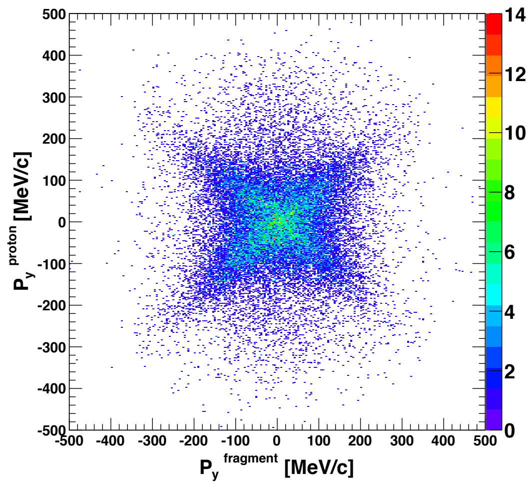



**Reconstructed from proton measurement**




Simulation



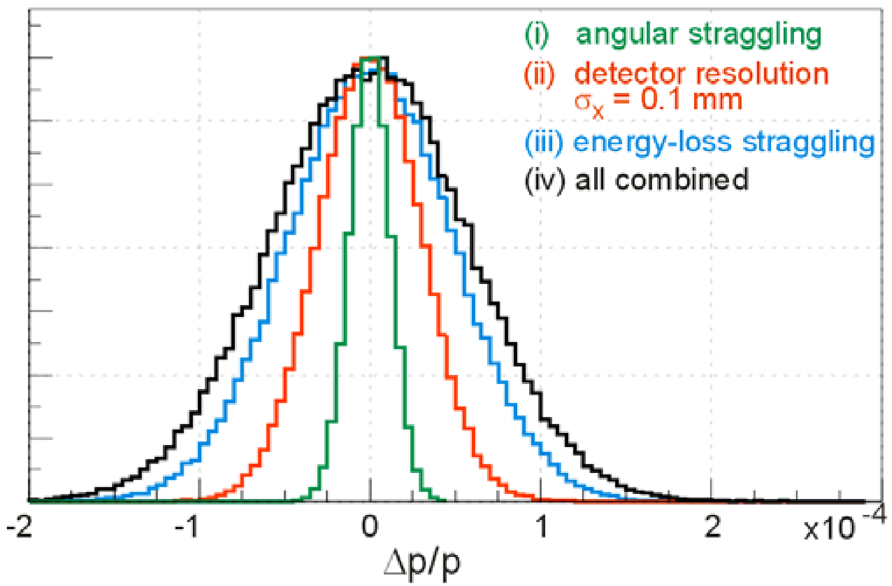



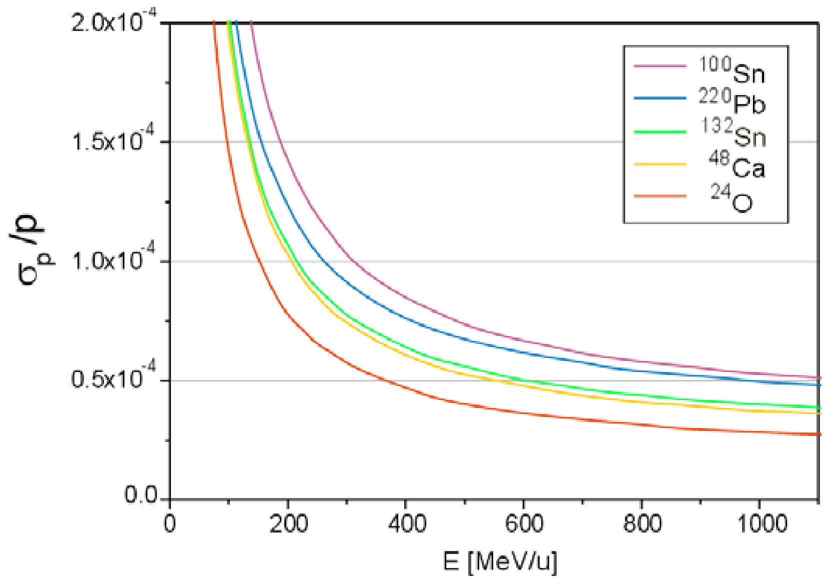

Measurement

Valerii Panin, PhD thesis, TU Darmstadt (2012)

# Resolution

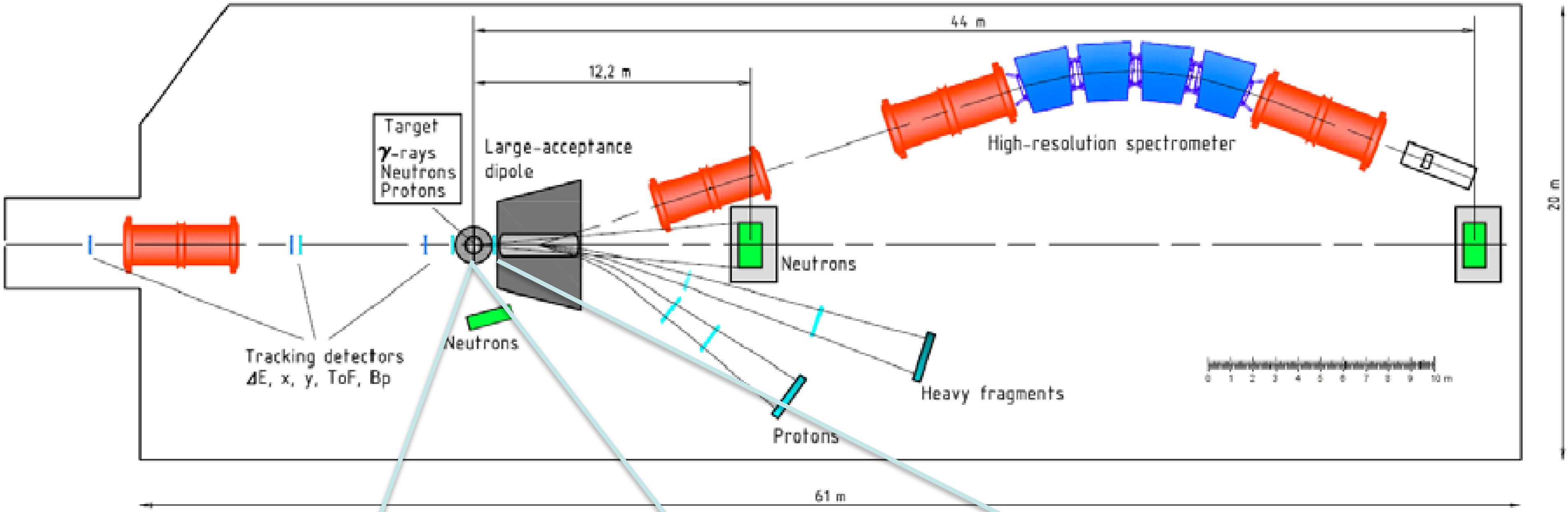
- 1 GeV/nucleon $^{220}$Pb: P=370 GeV/c
- Recoil momentum resolution: 37 MeV/c
- Recoil momentum width = 75,100,140,200,270 MeV/c (l=0,1,2,3,4)
- Thick lH target: location straggling unimportant due to vertex measurement (p,2p)

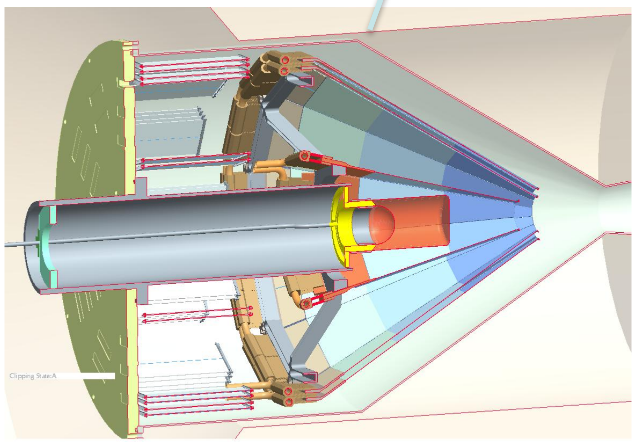


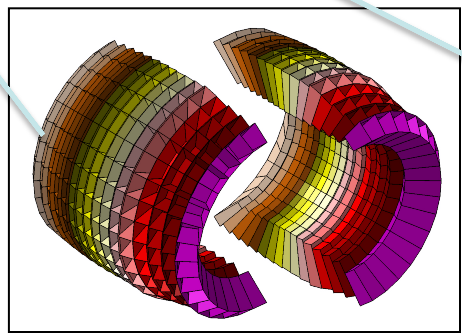



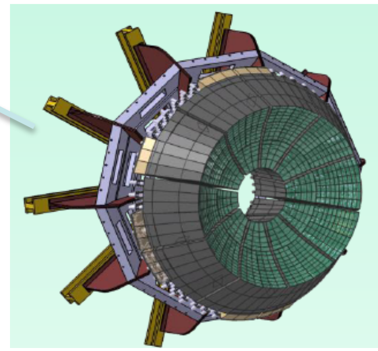

R. Zegers, H. Geissel, T. Aumann et al., ‘A high-resolution spectrometer for advanced nuclear structure and reaction studies at relativistic energies’

# (p,2p) and (p,pn) at R3B with high-resolution spectrometer







For heavy nuclei:
Excitation energy from invariant mass (HF+xn),
plus 2p kinematics
Precoil from HF )spectrometer) + 2 p kinematics

# Reactions to be studied at R3B

### A.4. Overview on subsystems

The following table gives an overview of the subsystems needed for the different type of experiments as indicated by crosses. In several cases, a detector might not necessarily be required but would, however, improve the quality. Those are marked with a cross in brackets.

Subsystems:

(1) Large-acceptance dipole
(2) High-resolution spectrometer
(3) Tracking detectors
(4) Proton tracking
(5) Large-area ToF wall
(6) Gamma spectrometer
(7) Target recoil detector
(8) Active target
(9) Low-energy neutron detector
(10) Neutron ToF spectrometer
(11) Multi-track detector

| Reaction/Physics | Subsystem | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Knockout | x | x | x | - | - | x | | - | - | x | - |
| Quasi-free scattering | x | x | x | (x) | - | x | x | - | - | x | - |
| Total-absorption meas. | x | (x) | x | - | - | - | - | - | - | - | - |
| (In-)elastic scattering | x | (x) | x | - | - | x[1)] | x[1)] | x | - | - | - |
| Electromagnetic exc. | x | (x) | x | x | - | x | - | - | - | x | - |
| Charge-exchange | x | (x) | x | - | - | - | - | - | x | x | - |
| Fission | x | x[2)] | x | - | x | x | - | - | - | x | x |
| Spallation | x | - | x | - | x | x | - | - | - | x | x |
| Projectile fragmentation | x | (x) | x | - | - | x | x | - | - | x | - |
| Multifragmentation | x | - | x | - | x | - | x | - | - | x | x |

← Intensity !
← Invariant mass !

[1)] The target recoil detector and calorimeter will be used for large-momentum transfer reactions only, low-energy recoils will be detected in the active target

[2)] For high precision (velocity) measurements the spectrometer is needed (only one fission fragment is detected). Kinematically complete measurements of fission will be done using the large-acceptance mode

R3B Technical Proposal, December 2005

# Physics and reactions with large acceptance or high resolution

- **Large-acceptance mode**
  - ✓ mostly reactions with light ions
    (acceptance of all fragments with very different rigidity / A/Z ratio)
  - ✓ mass resolution also for heavy fragments
  - ✓ longitudinal momentum measurement only for light ions
  - ✓ coincidence with neutrons, protons, tritons, alpha, ….
  - ✓ bending 18 degree for 15 Tm, 15 degree for 18 Tm

  ➔ QFS, elm. excitation, unbound nuclei, fission, spallation, multi-fragmentation…..

- **High-resolution mode**
  - ✓ recoil momentum resolution also for heavy fragments
  - ➔ knockout, spectroscopy (determination of angular momentum / spatial extension)
  - ➔ quasi-free knockout reactions with heavy nuclei
    also in coincidence with neutrons (deeply bound shells in heavy nuclei)
  - ✓ selection of reaction channel (spatial separation of fragments)
  - ➔ high-rate measurements
    (thin targets, small cross sections, elm. excitation, QFS, …)
  - ➔ trigger on fragment (e.g. knockout to bound A-1 ground state)
  - ✓ very good mass separation
  - ➔ elastic scattering, total-absorption measurements for heavy nuclei
  - ✓coincidence with neutrons ➔ invariant mass, QFS, charge-exchange,…

# Summary

## Broad physics programme for a high-resolution spectrometer at R3B

- $\Delta B\rho / B\rho \sim 10^{-4}$, max $B\rho = 15$ Tm (e.g. 1 GeV/nucleon $^{220}Pb$)
- Coincidence with neutrons
  e.g. QFS, elm. Excitation with high intensities / thin targets
- Measurement of recoil momentum for heavy nuclei
  e.g. knockout, QFS
- Spatial separation of fragment
  allows trigger without other detectors, basis for high-intensity measurements
- Achromatic target focus after three-stage separation of Super-FRS
  placement of high-efficiency gamma and particle detection around the target