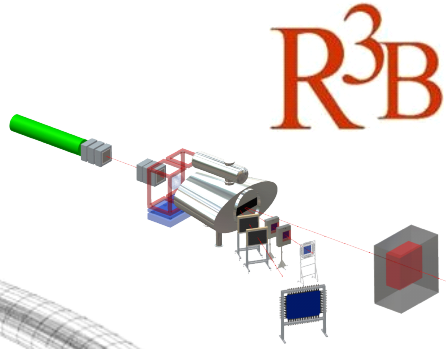
First Experiments with R3B



Thomas Aumann

TECHNISCHE UNIVERSITÄT DARMSTADT
HIC for FAIR Helmholtz International Center
GSI
NAVI Nuclear Astrophysics Virtual Institute

October17th 2014

International Conference on Science and Technology for FAIR in Europe 2014

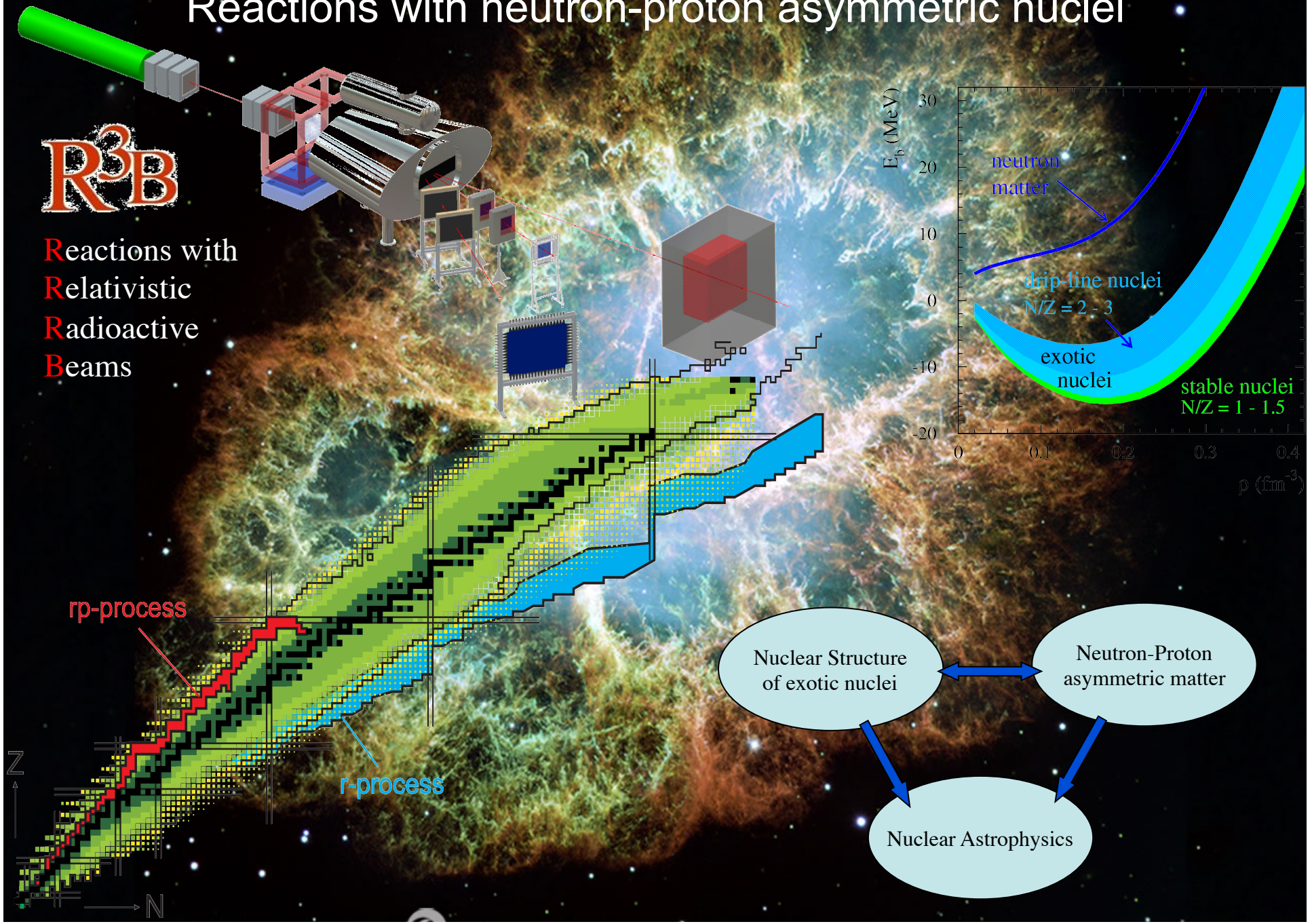
Worms

GEFÖRDERT VOM

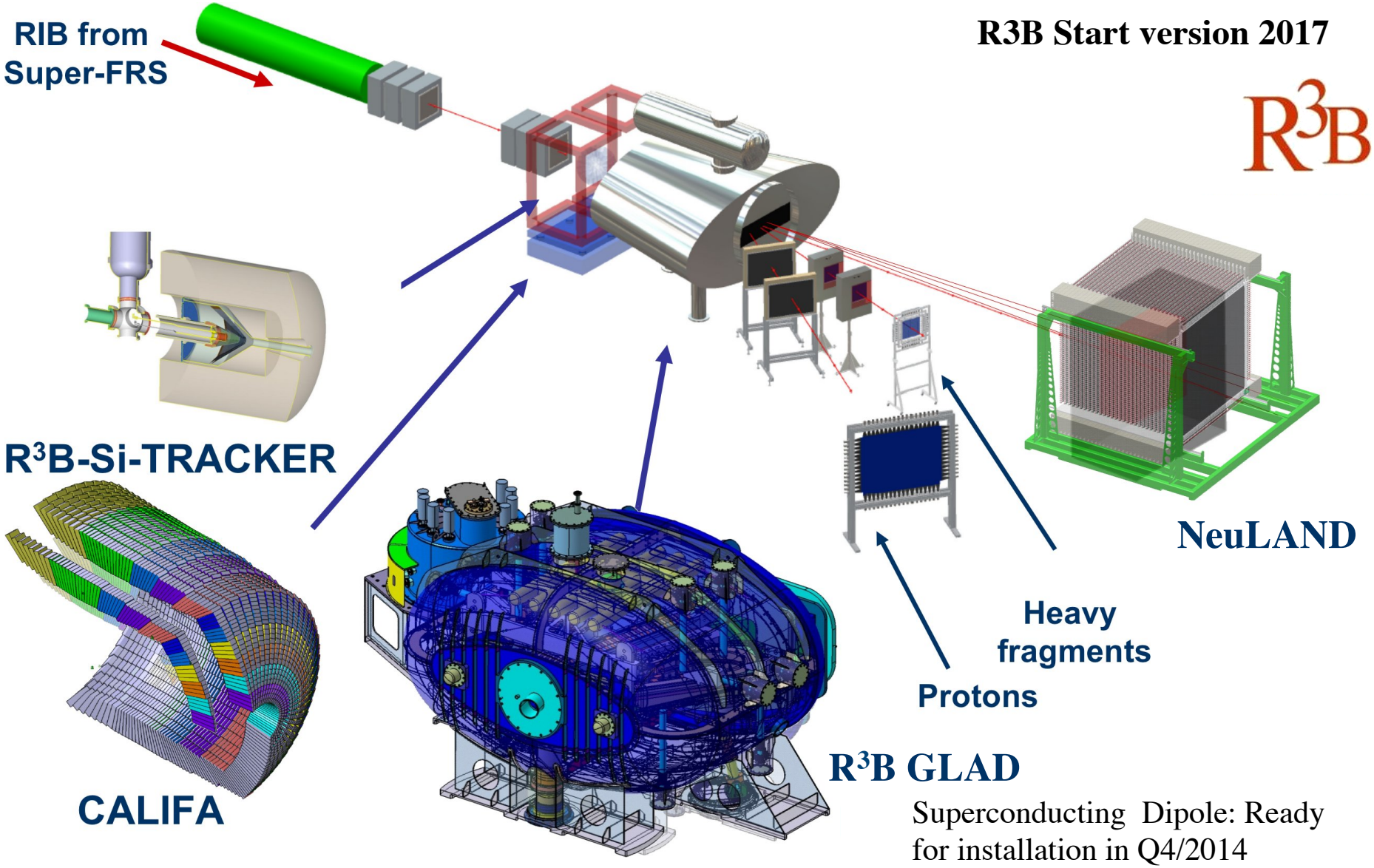
Bundesministerium
für Bildung
und Forschung

Supported by the BMBF under contract no 05P12RDFN8

Reactions with neutron-proton asymmetric nuclei



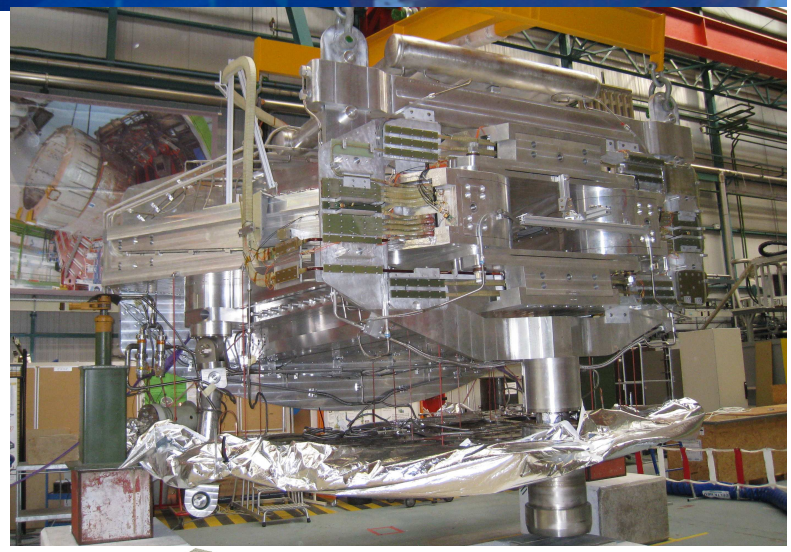
Reactions with Relativistic Radioactive Beams



Superconducting Dipole: Ready for installation in Q4/2014
Construction by CEA Saclay

Status

Major achievements



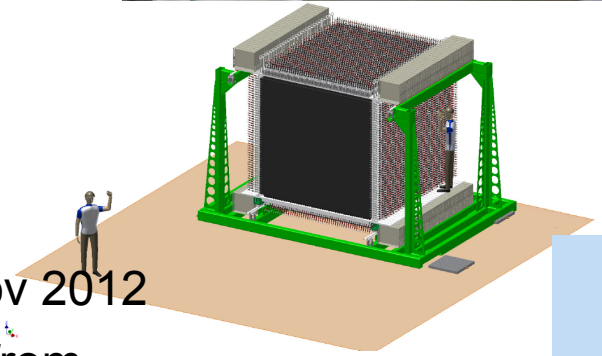
Large-acceptance dipole GLAD

✓ Cold mass ready and inserted in test cryostat at Saclay

✓ Final cryostat in construction

✓ Delivery of magnet to GSI end of 2014

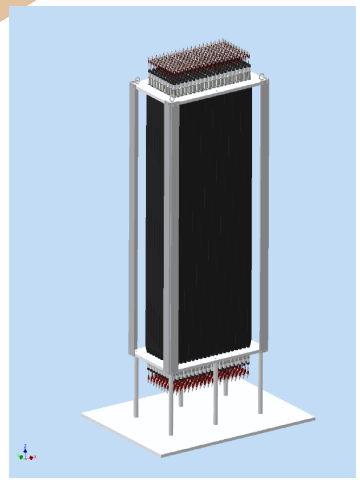
Neutron Detector NeuLAND



✓ Design finalized
modular active detector of 3000 scintillator bars; 250x250x300cm^3 active volume

✓ TDR submitted to FAIR and accepted in Nov 2012

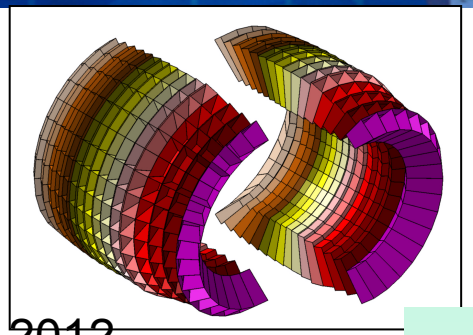
✓ Experiment with mono-energetic neutrons from deuteron breakup performed in Nov 2012:
200 modules (400 PM channels) in final design mounted and tested



✓ Construction of 20% detector for 2014 completed
First five double-plane ready (commissioning with beam Oct2014)

Status

Major achievements

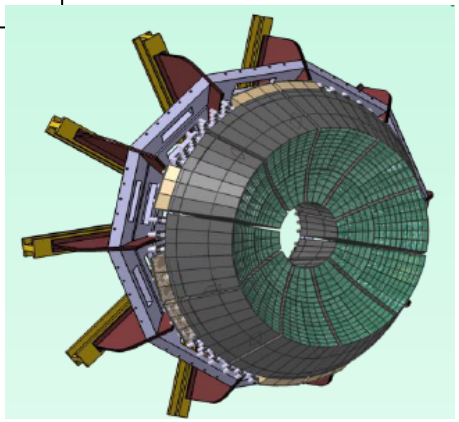


Photon- and particle calorimeter CALIFA

✓ Design of barrel part finalized
1952 CsI crystals with APD readout

✓ TDR submitted to FAIR and accepted in Nov 2012

✓ R&D on forward end-cup concluded, TDR in preparation
phoswich concept of LaBr3-LaCl3 crystals

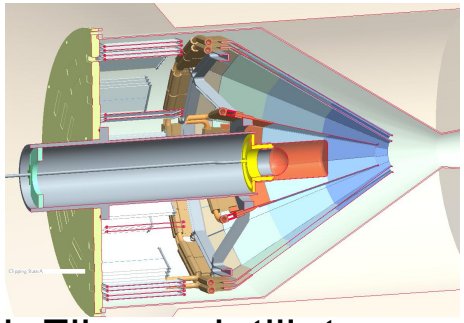


Target Recoil Tracking Detector

✓ Design finalized

✓ Construction started

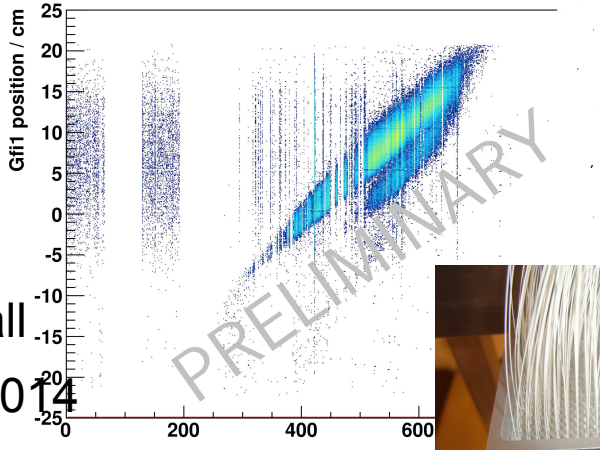
✓ Project fully funded and
lead by UK consortium

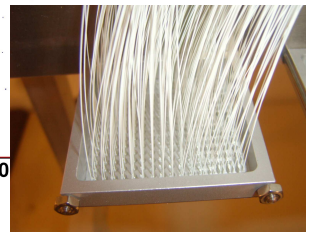


Tracking Detectors

R3B tracking system designed: Fiber-scintillators,

Segmented resistive Si-detectors, large-area ToF wall





✓ Successful tests with beams at GSI in 2012 and 2014

✓ Construction of final detection system started

Schedule and first experiments

2013 Installation of infrastructure in Cave C for GLAD (He cryo-system, power supply)
Delivery and installation of superconducting dipole GLAD (expected Q4/2014)

2014 Installation of 20% detectors NeuLAND and CALIFA
Commissioning run in Q3/2014 (happened last week!)

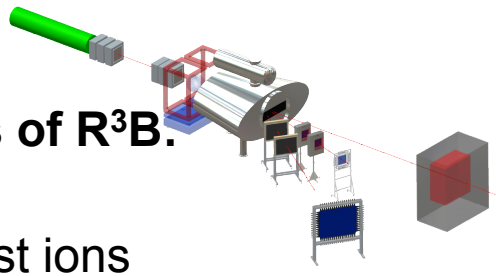
2015/16 Construction and installation of detector components

2017 Commissioning of R3B setup and first physics run at GSI

2018 Physics program at Cave C

2019 Installation of experimental setup at FAIR site including superconducting triplet

2020 Commissioning and first experiments at Super FRS



Experiments in (2018) 2020 will make use of uniqueness of R^{3}B:

- Reactions at high beam energies up to 1 GeV/nucleon
- Tracking and identification capability even for the heaviest ions
- Multi-neutron tracking capability, high-efficiency calorimeter

➡ **Experiments possible for the first time:**

- 4 neutron decays beyond the drip-line and for heavier n-rich isotopes
- Kinematically complete measurements of quasi-free nucleon knockout reactions
- Electric dipole and quadrupole response of Sn nuclei beyond N=82, and of neutron-rich Pb isotopes

First experiments at Cave C 2017 +

R3B Status: GLAD installed
Full heavy-ion tracking system
Target Recoil detector complete
CALIFA available to a large fraction
NeuLAND available to a large fraction
Active Target

→ Novel Instrumentation at place, 1 GeV/u beams possible for the first time

1. Dipole strength function of halo nuclei up to 30 MeV excitation energy
2. Quasi-free scattering at large momentum transfer and short-range tensor correlations
3. Fission
   - Fission Barriers of exotic nuclei measured by (p,2p) induced fission
   - New deformed shell structures in the electromagnetically induced fission of neutron deficient pre-actinides
   - Excitation energy sharing in the electromagnetically induced fission of actinides
4. Spectroscopy of 2^+ states of heavy neutron-rich nuclei
5. Elastic and inelastic scattering using the active target

First experiments at Cave C 2017 +

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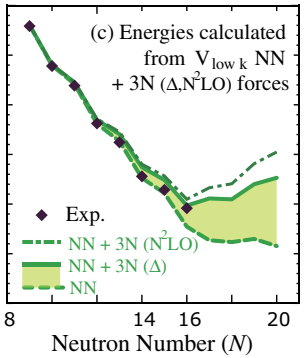
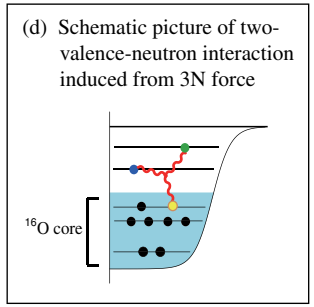
Quasi-free scattering in inverse kinematics with high-energy radioactive beams

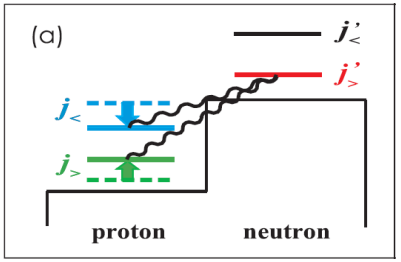
Quasi-free knockout reactions
(p,2p), (p,pn), (p,2p,n), (p,pd), (p,pα), (p,2p)fission

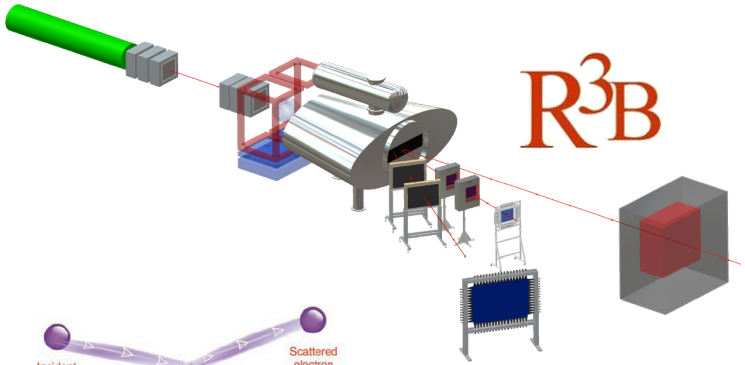
- Evolution of Shell structure
- Fission barriers
- Nucleon-Nucleon Correlations
  (short-range tensor correlations)
- Cluster structure
- States beyond the neutron dripline



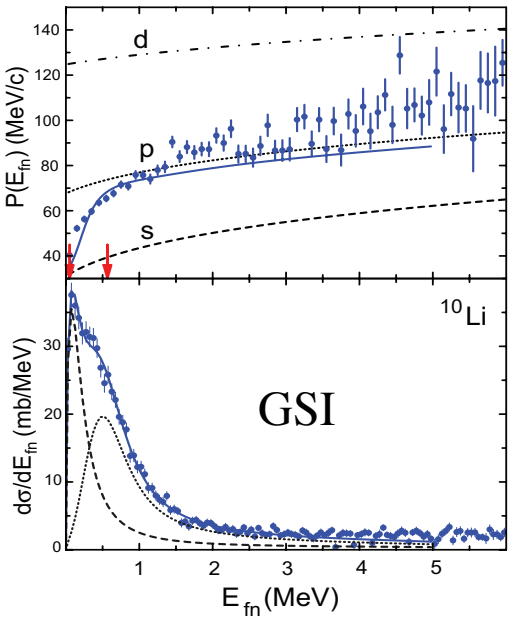


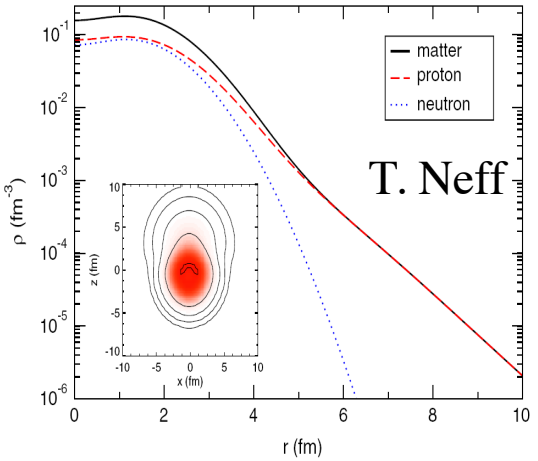
Otsuka et al.



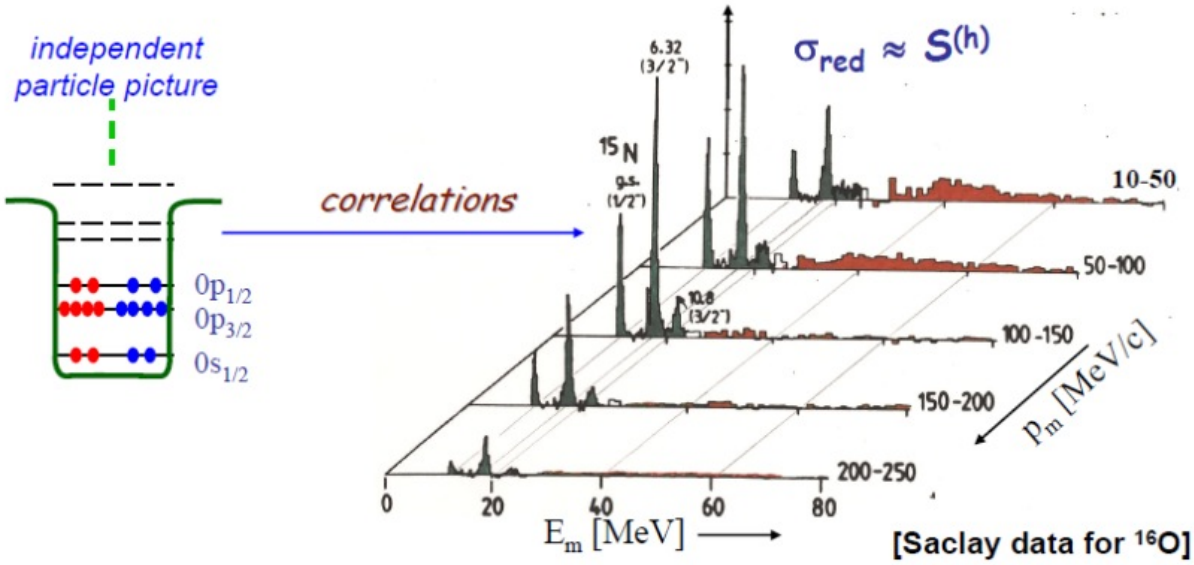


Jlab

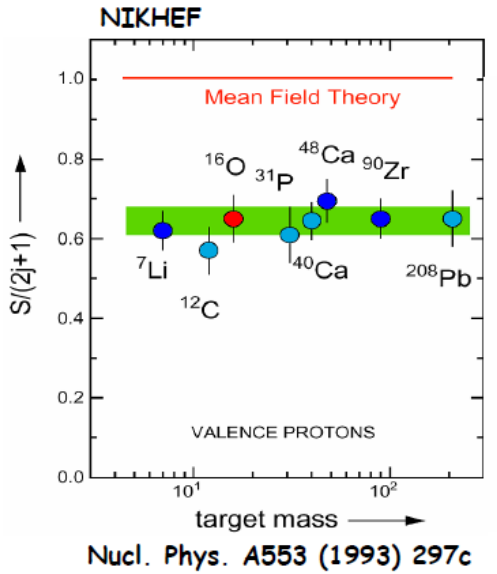




Single-particle structure and correlations



[Saclay data for ^{16}O]



Nucl. Phys. A553 (1993) 297c

Deviation from the independent-particle picture:

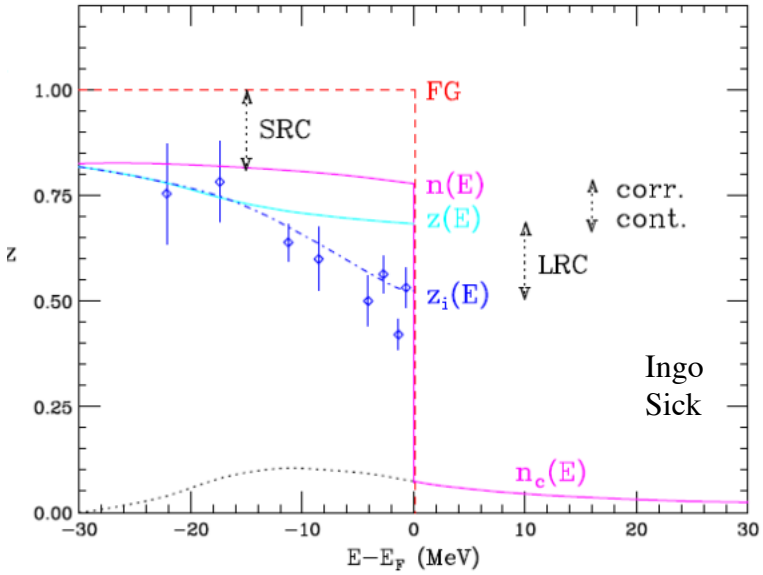
Correlations: Configuration mixing,

Coupling to collective phonons

Short-range and tensor correlations

→ high momenta

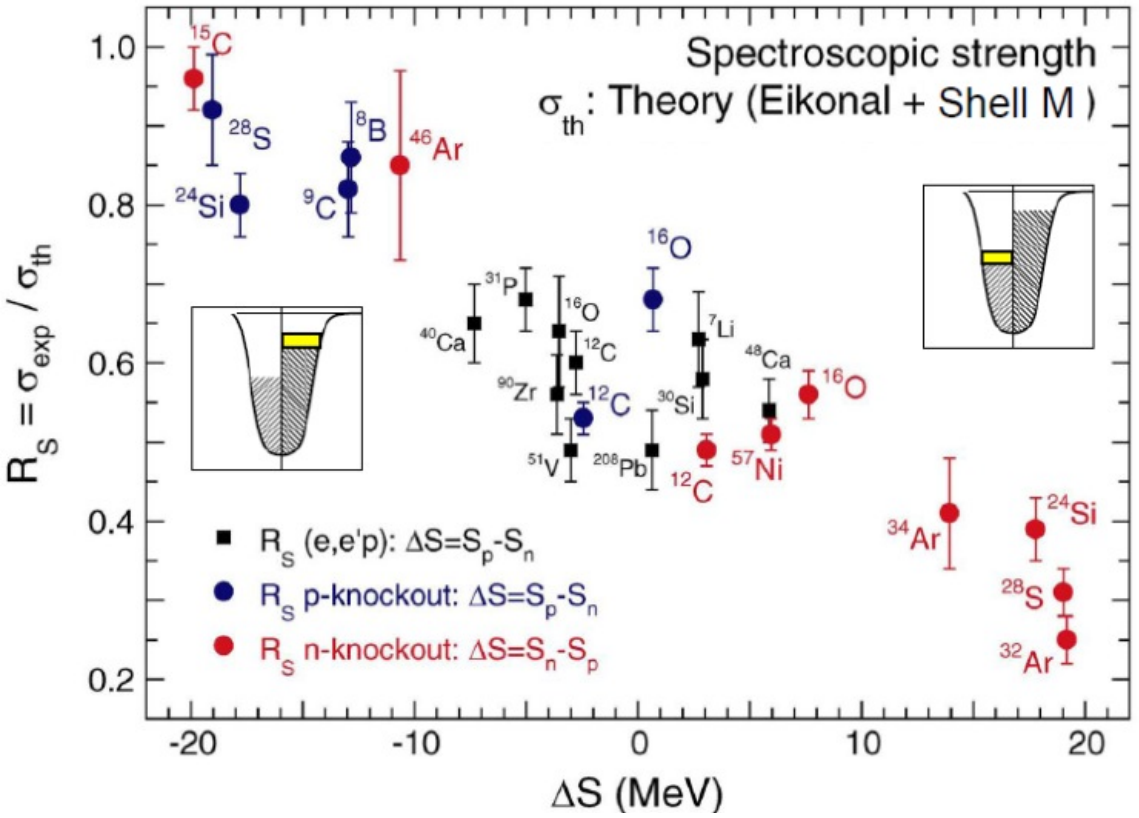
→ reduced single-particle strength



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

weakly bound nucleons

strongly bound nucleons



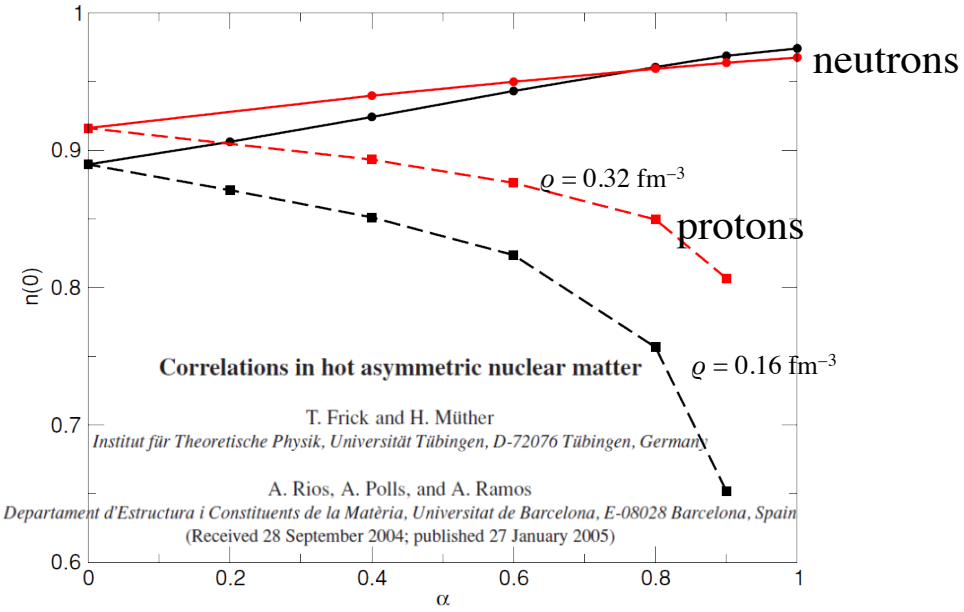
?

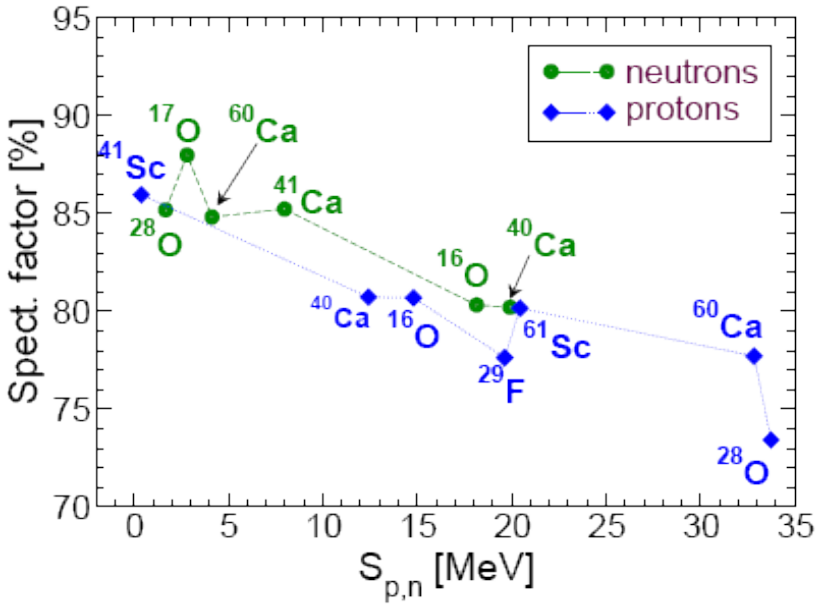
Origin unclear

?

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

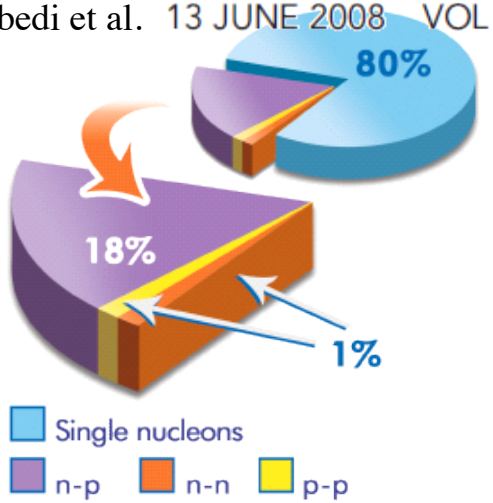
Correlations in asymmetric nuclei and nuclear matter

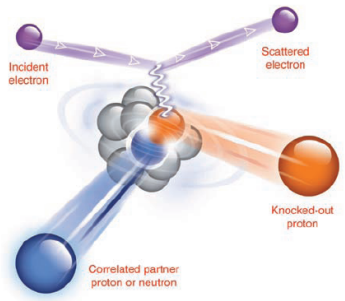




Probing Cold Dense Nuclear Matter

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

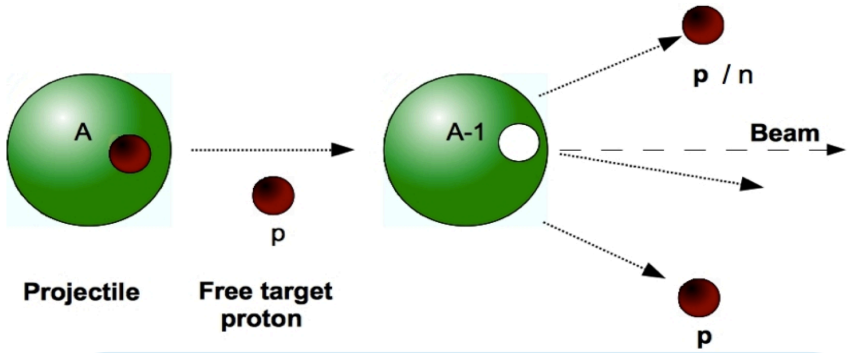
C. Barbieri

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

W. H. Dickhoff

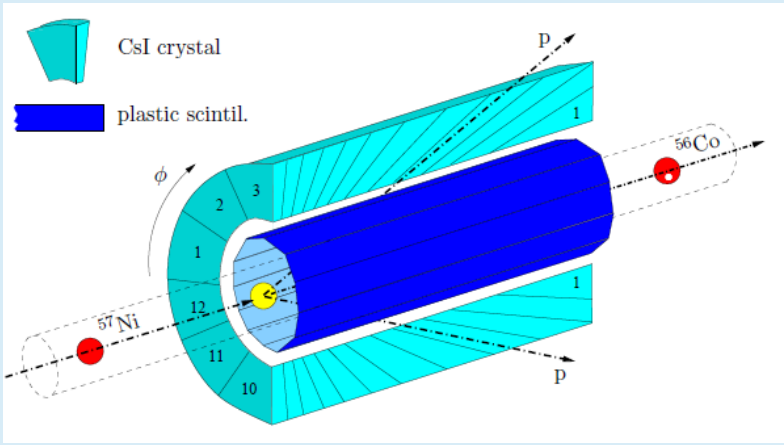
Department of Physics, Washington University, St.Louis, Missouri 63130, USA

Detection System



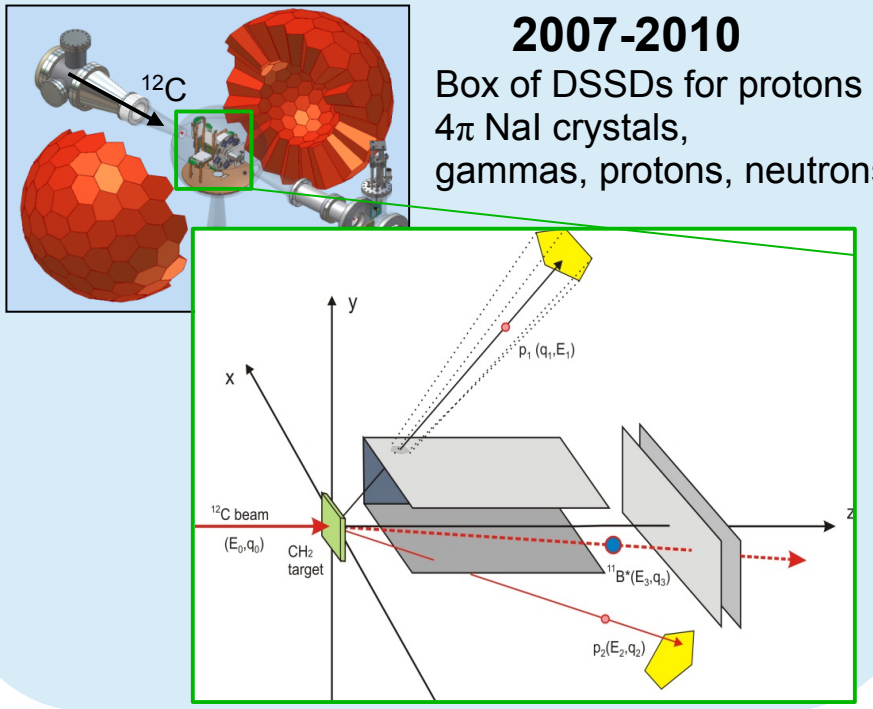
2005

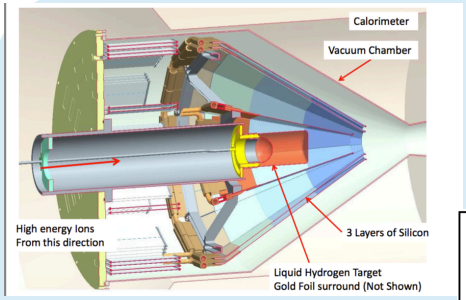
Plastic paddles for proton trigger
4π CsI crystals for gammas and angular measurements of protons and neutrons



2007-2010

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

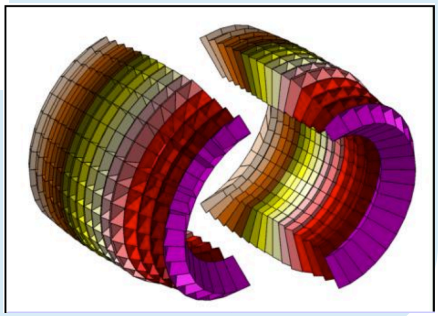




Si Tracker

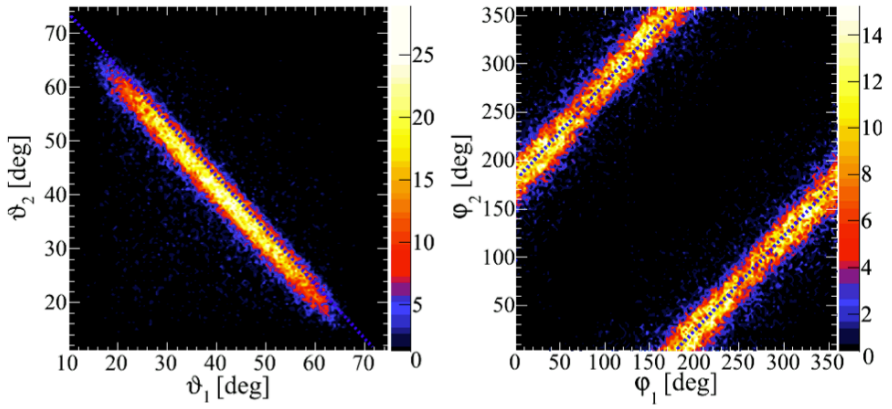
Future setup

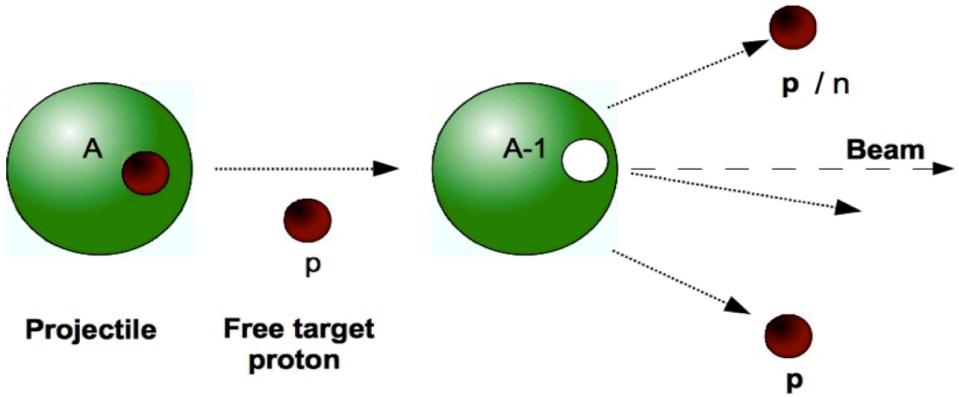
CALIFA



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

Strong angular correlations of the two nucleons

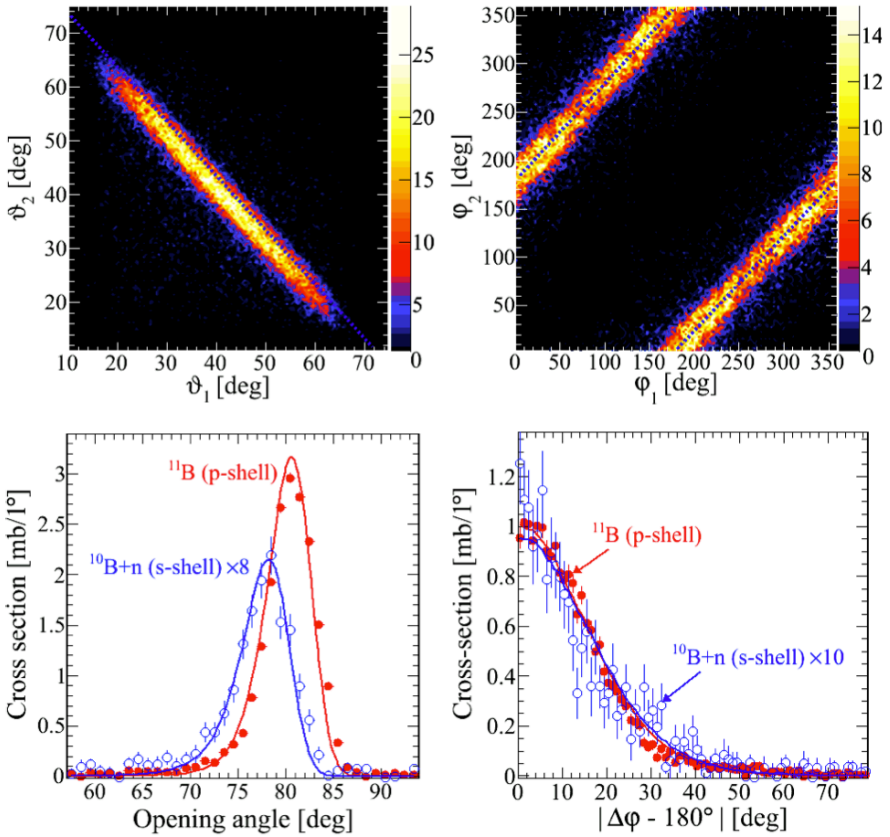




Analysis by V. Panin

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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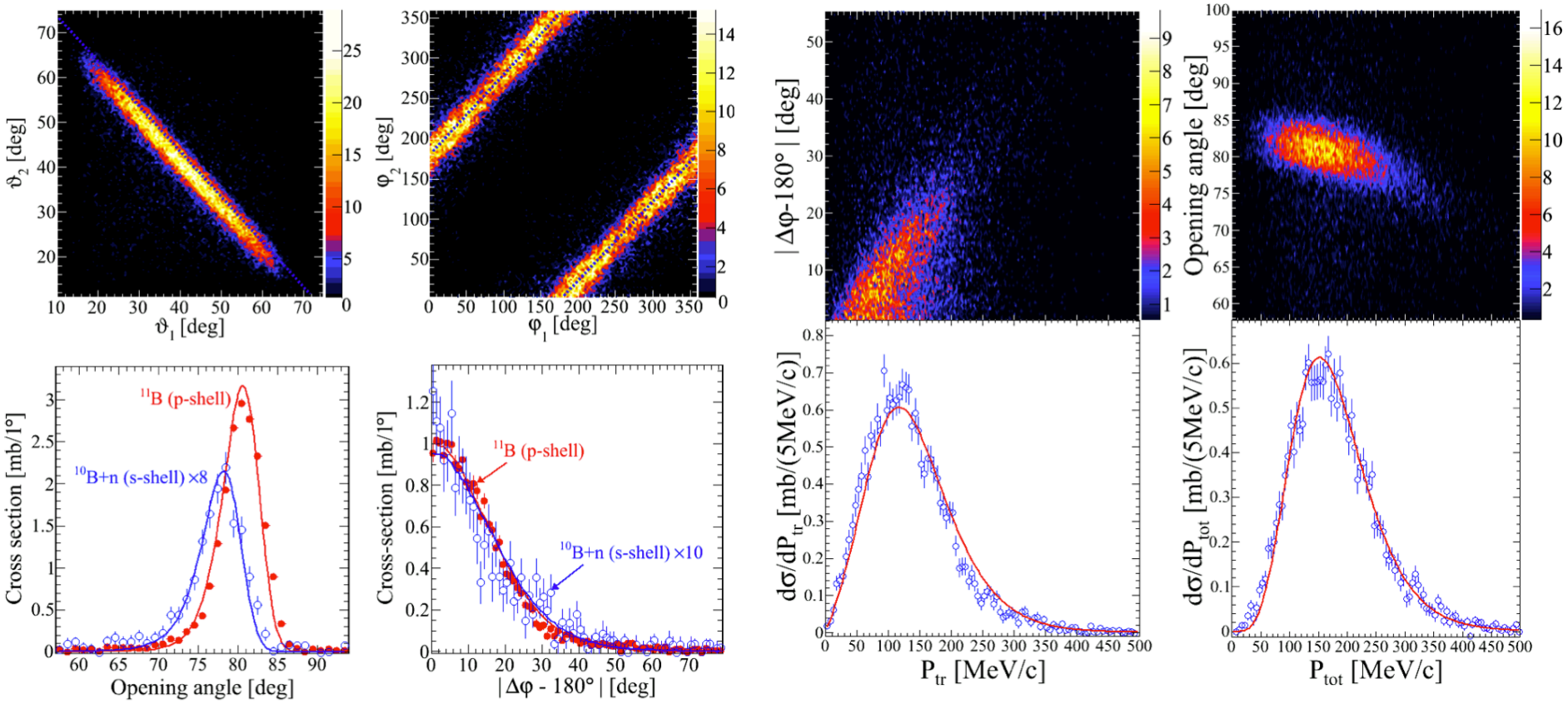
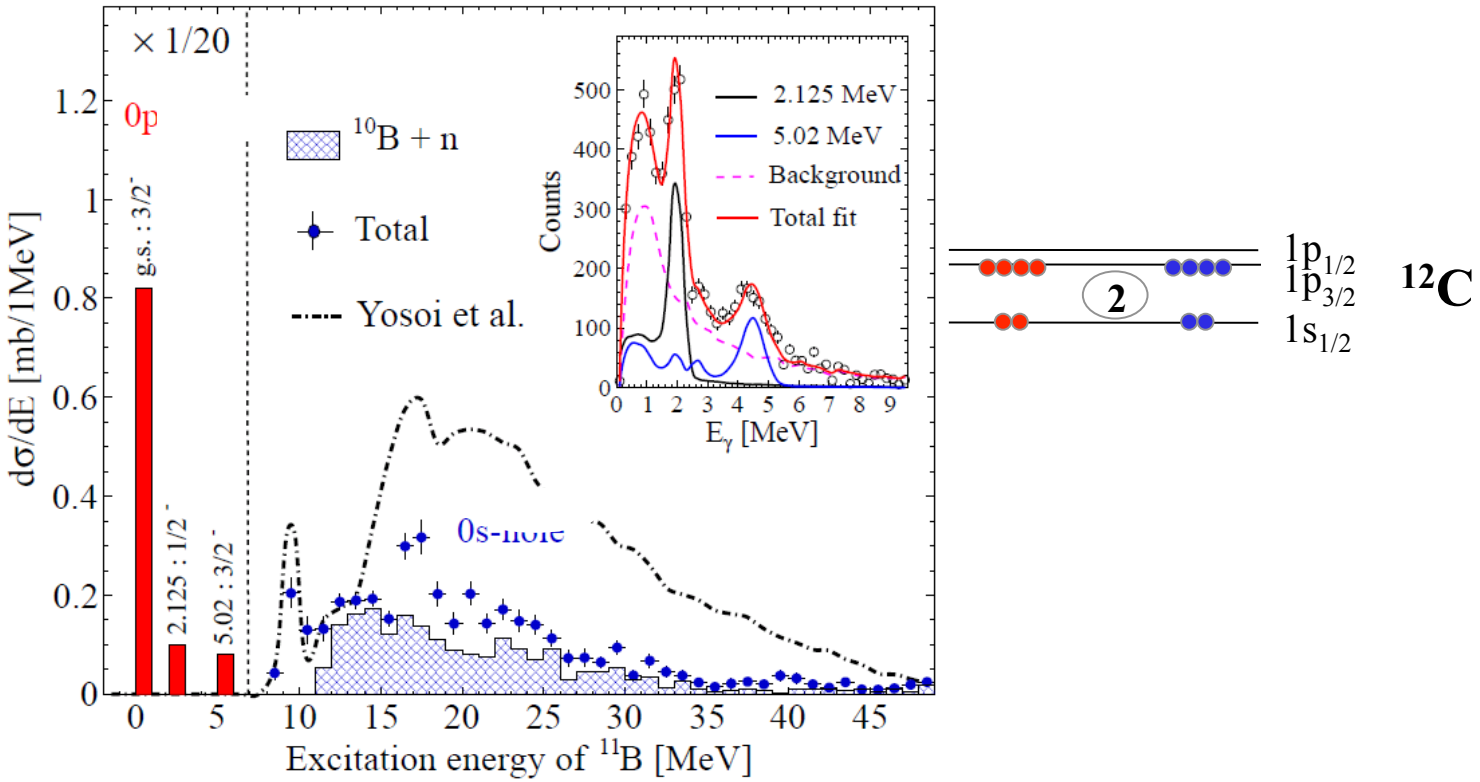


Analysis by V. Panin

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



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

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

Analysis by V. Panin

First experiments at FAIR 2020 +

Status: R3B completed (except high-resolution spectrometer)

1. Dipole response of heavy neutron-rich beams
   (Pygmy, GDR, polarizability, symmetry energy)
   Day-1: $^{208\text{-}218}$Pb
   Day-2: $^{220\text{-}224}$Pb (when design intensity is reached)

2. Dipole response (Pygmy, GDR, polarizability, symmetryenergy)
   of very neutron-rich Sn isotopes (beyond N=82) in the r-process path

3. Multi-neutron decays

4. Quasi-free scattering reactions with nuclei of extreme N-Z
5. Quasi-free scattering at large momentum transfer and short-ranged tensor correlations as a function of isospin
6. Elastic and inelastic scattering using the active target
7. Spectroscopy of 2^+ states of heavy neutron-rich nuclei
8. Spectroscopy of ^{100}Sn

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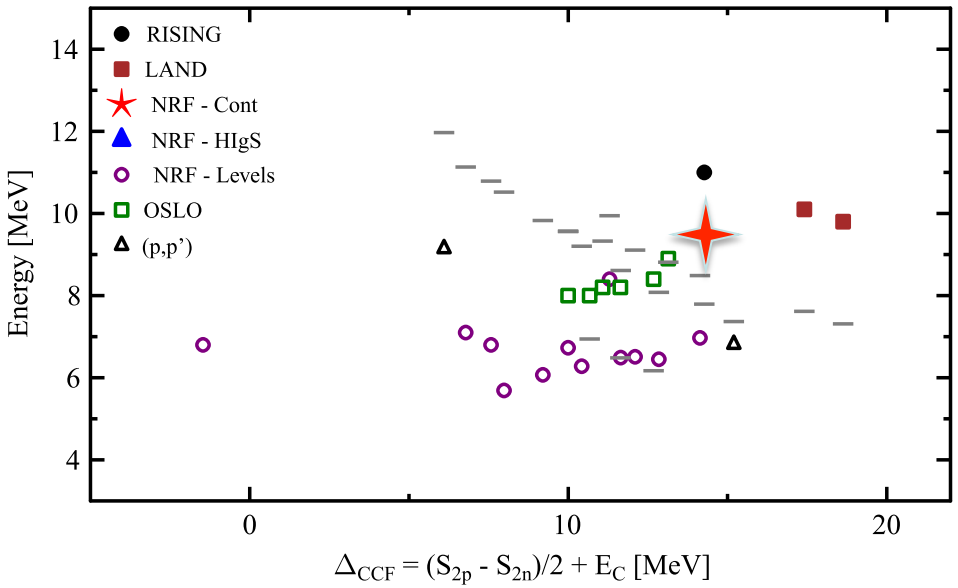
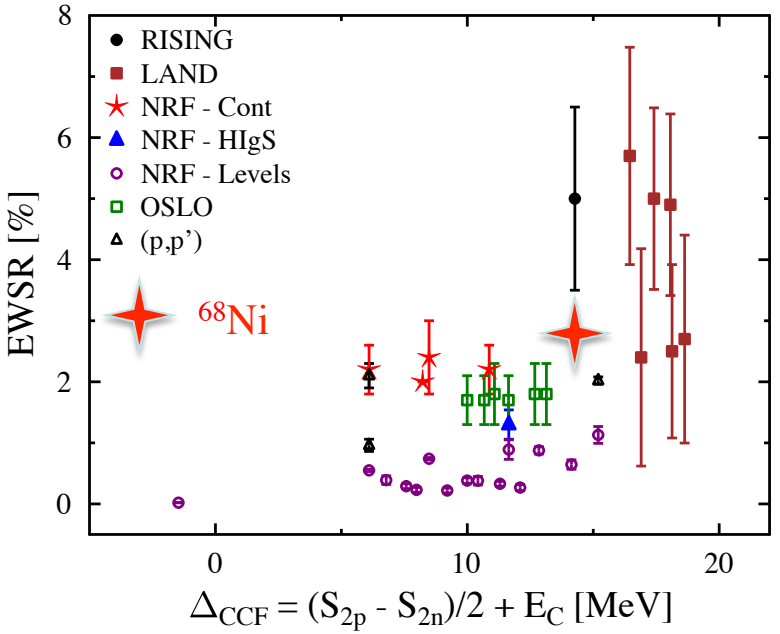
Systematics of Pygmy dipole strength ?



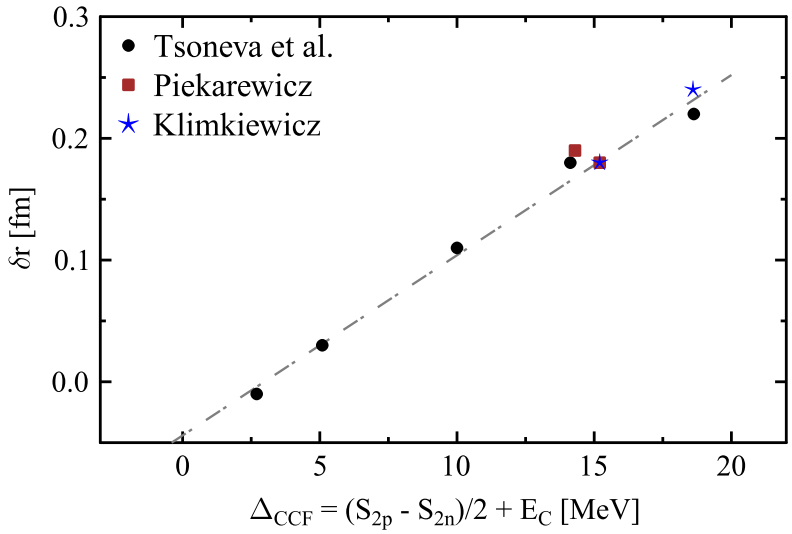


Review

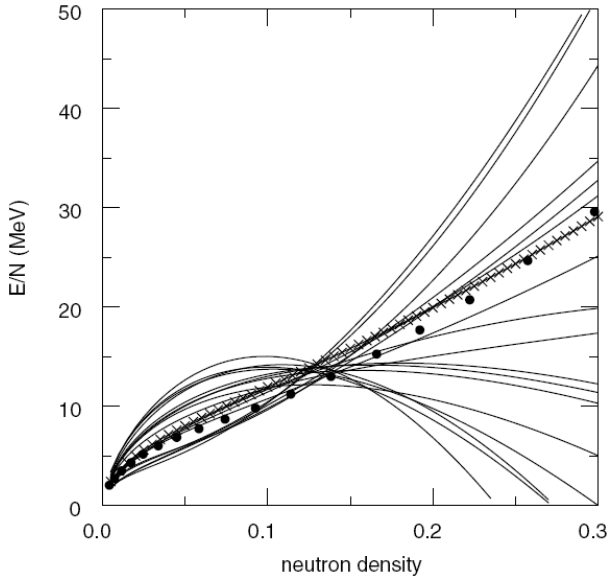
Experimental studies of the Pygmy Dipole Resonance

D. Savran [a,b,*], T. Aumann [c,d], A. Zilges [e]

Progress in Particle and Nuclear Physics 70 (2013) 210–245



Symmetry energy $S_2(\rho)$ and neutron skin in ^{208}Pb

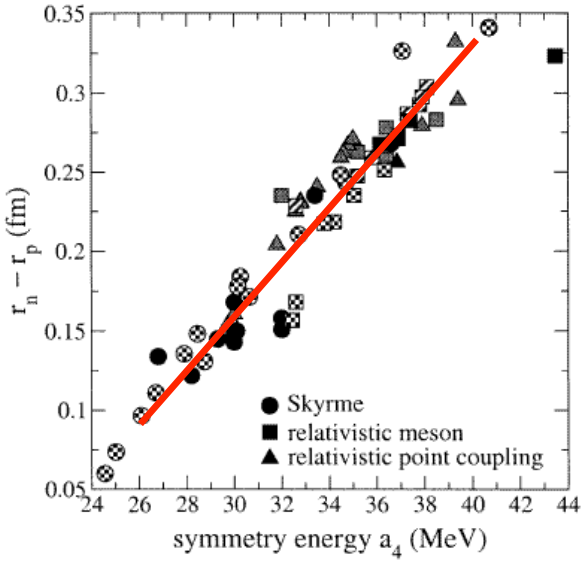


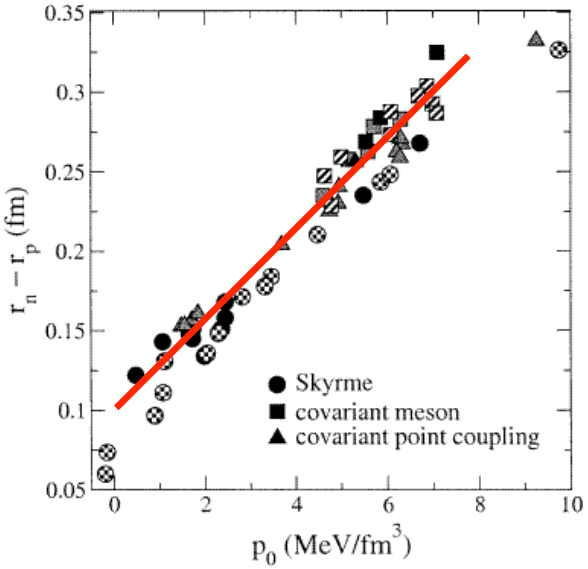
$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + O(\alpha^4),\ \alpha = \frac{N-Z}{A}$$

$$S_2(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\alpha)}{\partial \alpha^2}\bigg|_{\alpha=0} =$$

$$= a_4 + \frac{p_0}{\rho_0^2}(\rho-\rho_0) + \frac{\Delta K_0}{18\rho_0^2}(\rho-\rho_0)^2 + \ldots$$

Alex Brown,
PRL 85 (2000) 5296



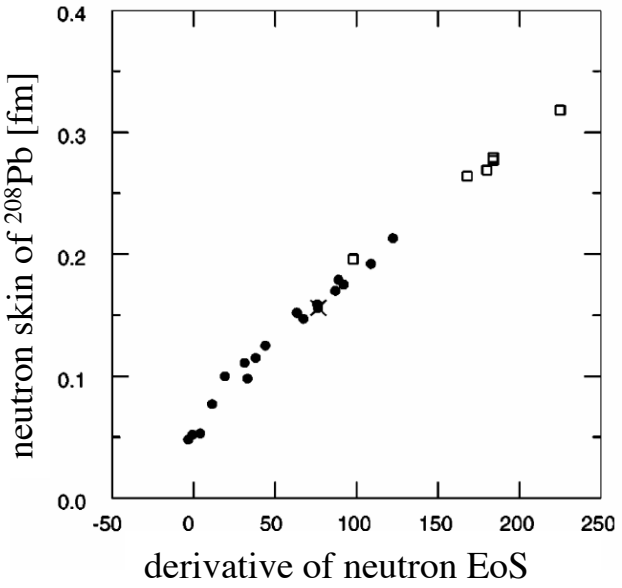


R.J.Furnstahl
NPA 706 (2002) 85-110

• strong <u>linear</u> correlation between neutron skin thickness and parameters **a_4, p_0**

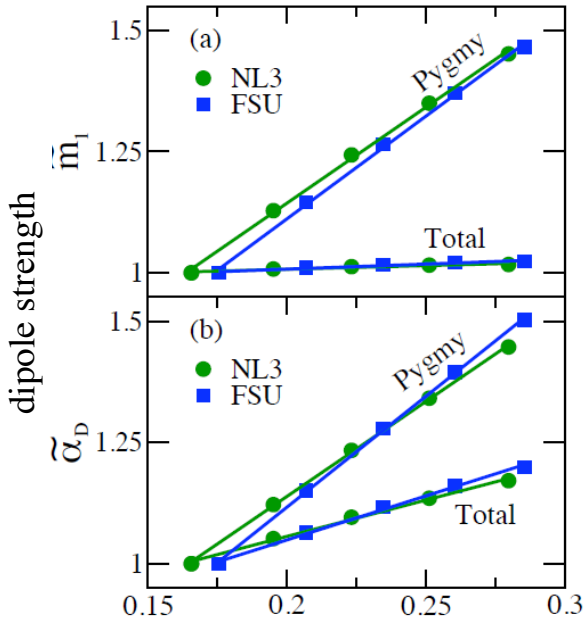
Symmetry energy and dipole response

neutron-skin thickness
dipole response

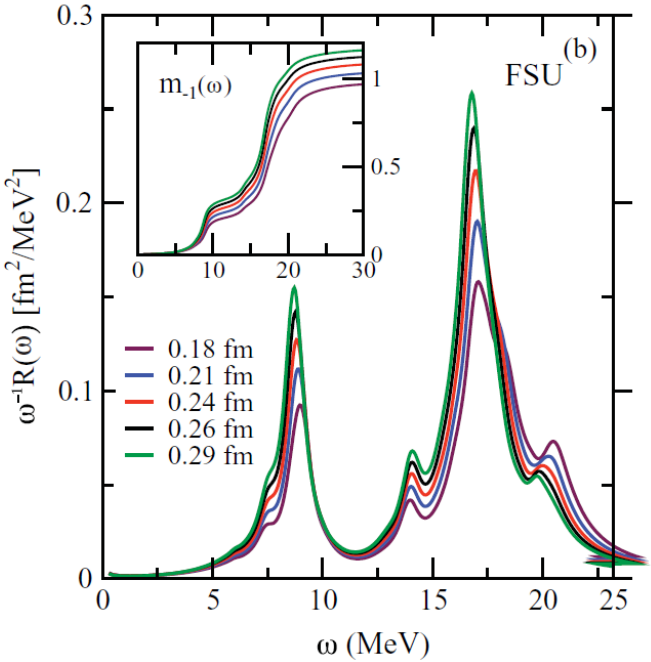


*S. Typel and B.A. Brown, Phys. Rev. C **64** (2001) 027302*

density dependence of
symmetry energy



properties of
neutron-rich matter



*J. Piekarewicz,PRC **83,** 034319 (2011)*

n-skin from Pygmy strength → A. Klimkiewicz et al., PRC 76 (2007) 051603(R)
A. Carbone et al., PRC 81 (2010) 041301(R)

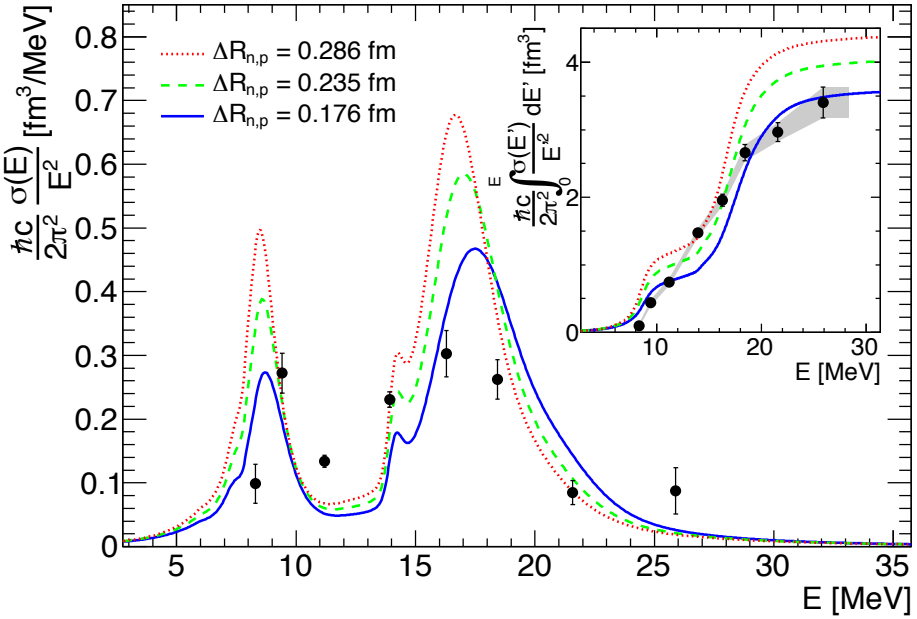
n-skin from polarizability → P.-G. Reinhard, W. Nazarewicz, PRC 81 (2010) 051303(R)
A. Tamii et al., Phys. Rev. Lett. 107 (2011) 062502.

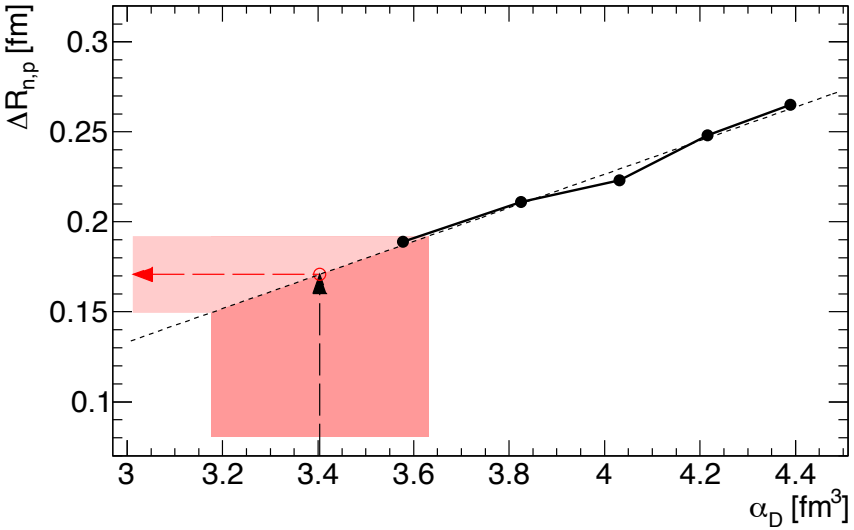
First measurement of the dipole polarizability for a short-lived nucleus

Dipole response of neutron-proton asymmetric nuclei

Pygmy- and Giant-Resonance and dipole polarizability of ^{68}Ni

➔ **Neutron-skin thickness, Symmetry-energy**





Neutron-skin thickness
$\Delta R_{n,p}$ = 0.175(21) fm

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma(E)}{E^2} dE$$

D. Rossi et al., Phys. Rev. Lett. 111 (2013) 242503

Conclusion

- R3B construction well on track
  Successful commissioning of already constructed detector components done

- **Day 0 (2017+)**

  New instrumentation including superconducting dipole will be available in Cave C for experiments

  → Unique experimental program possible already at Cave C

- **Day 1 (2020+)**

  R3B completed and ready for beams at FAIR

  → Physics program with exotic beams from Super-FRS