Reactions with relativistic radioactive beams (R^3B) in NUSTAR

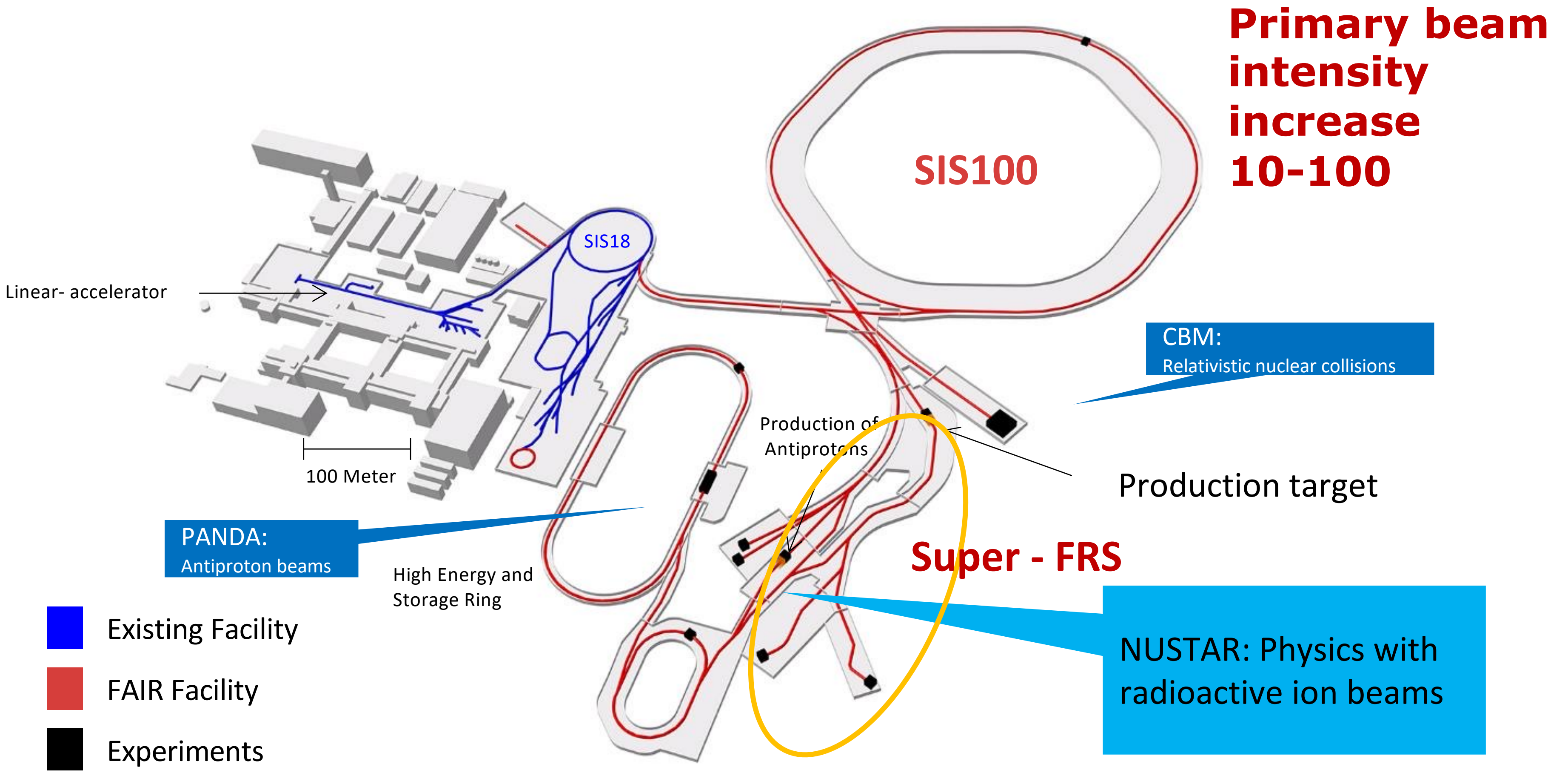
Andreas Heinz for the R^3B collaboration

With a lot of material from J. Cederkäll, V. Panin, H. Simon, …

R3B

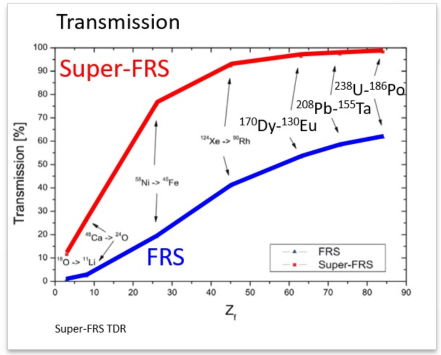
FAIR
Phase 0
Research Program

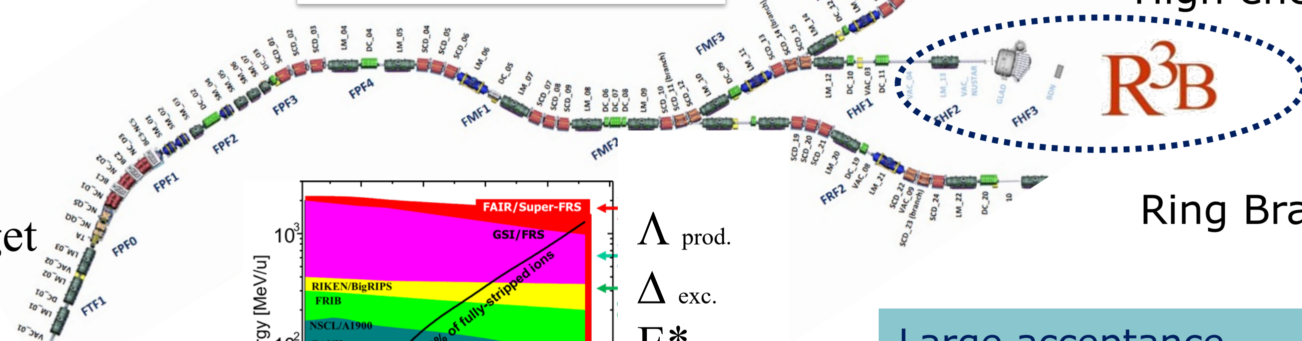
Radioactive beams at FAIR



Super-FRS: workhorse for NUSTAR

Production via projectile fragmentation and fragmentation -fission

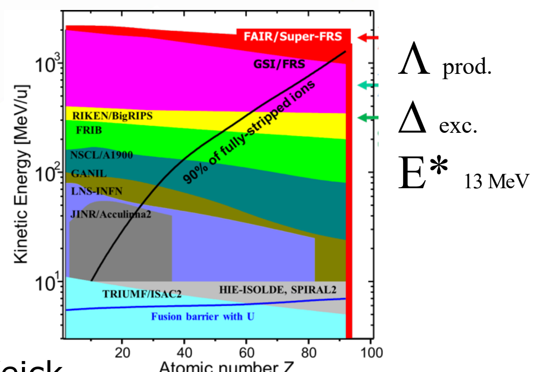




Low energy Branch with Energy buncher

High energy Branch

Ring Branch



Technical Design Report:
H. Geissel, M. Winkler, H. Weick, et al. (2009)

Large acceptance
High rigidity, minimized losses
→ Thick production targets
→ Most effective use of primary beam for experiments

R^3B: Reactions with relativistic radiatoactive beams

The general idea: collide radioactive beams with a secondary target for kinematically complete measurements - usually in inverse kinematics.

This requires:

Incomming particle ID => tracking, ΔE and ToF detectors.

Gammas, protons, neutrons around the target => CALIFA

Identify reaction fragments => GLAD, tracking detectors, ToF wall

Neutrons in forward direction =>NeuLAND

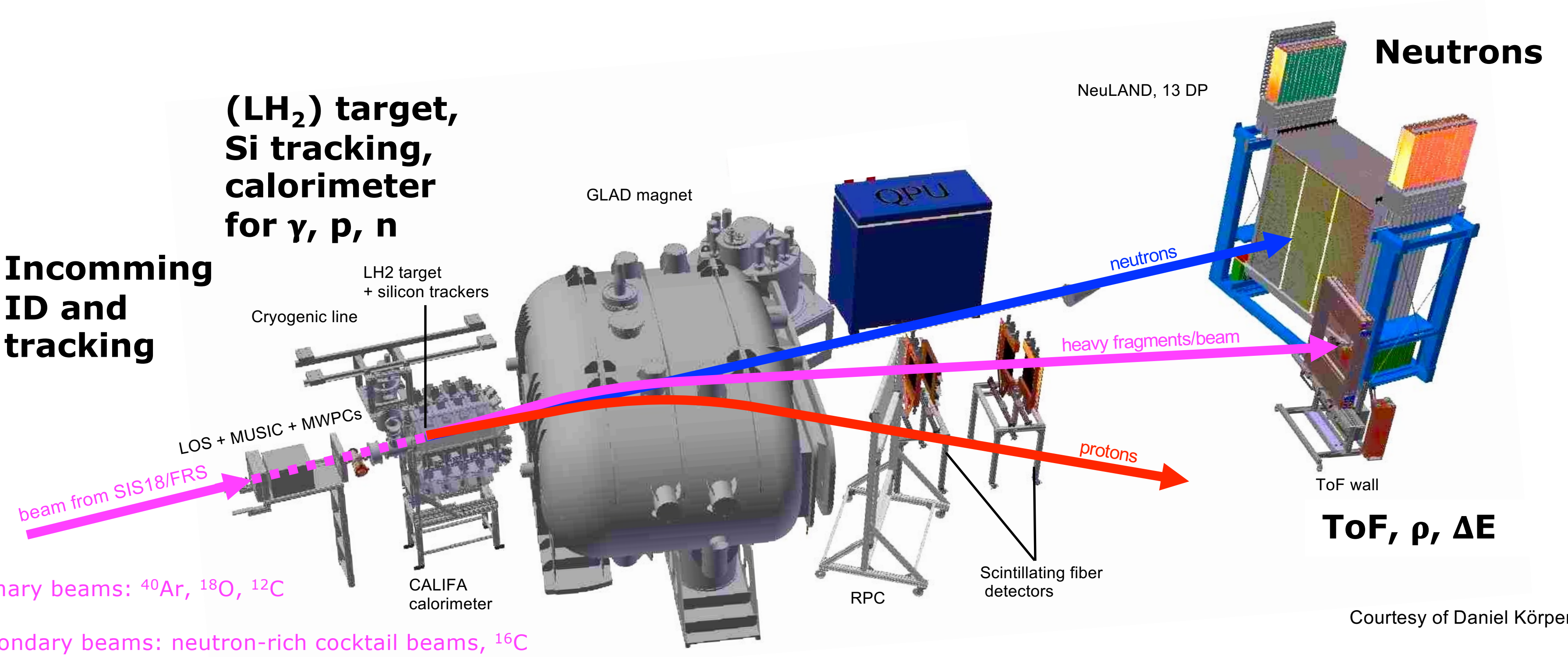
Protons in forward direction => mRPC (Resistive Plate Chamber)

The R³B setup in 2022

Bρ-ΔE-ToF
ΔE → Z
ToF → β

$$\Rightarrow B\rho = \frac{m_0 \gamma \beta}{Z} \Rightarrow$$

Identification of radioactive beam and secondary fragment

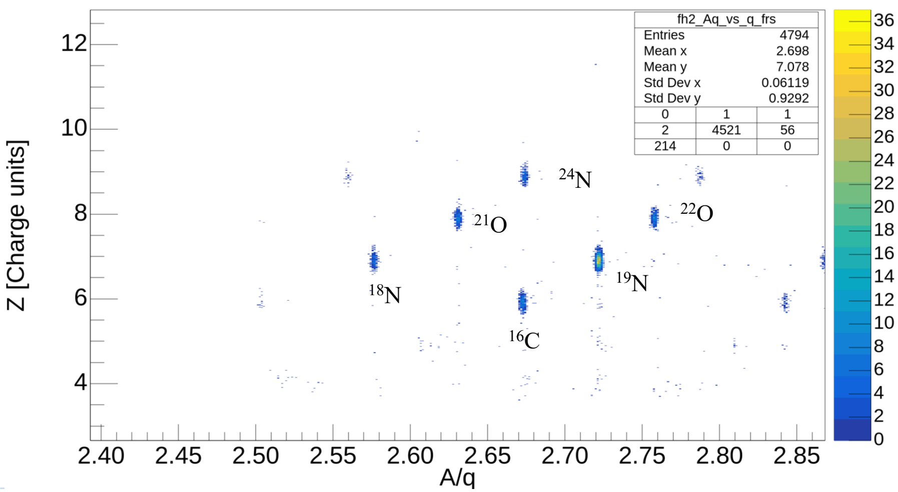


Primary beams: ^{40}Ar, ^{18}O, ^{12}C

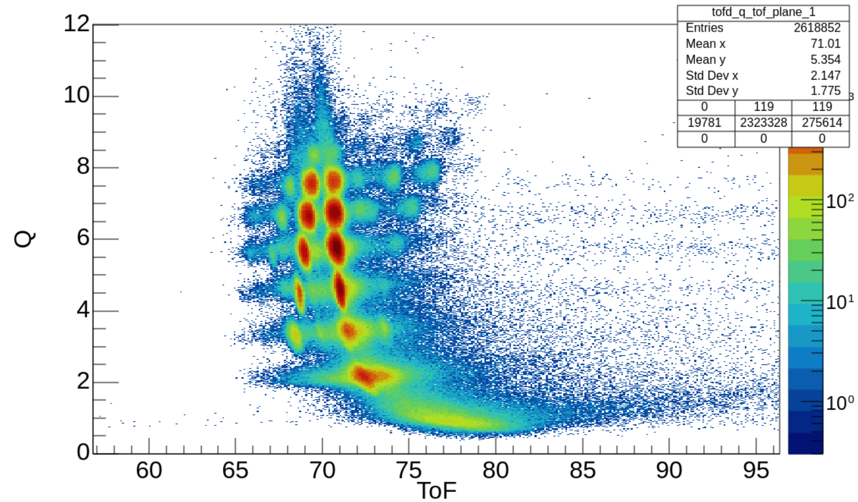
Secondary beams: neutron-rich cocktail beams, ^{16}C

Example for beam and secondary fragment identification

Incoming beam PID from FRS (S2-LOS)



Outgoing beam PID behind GLAD (TOFD)

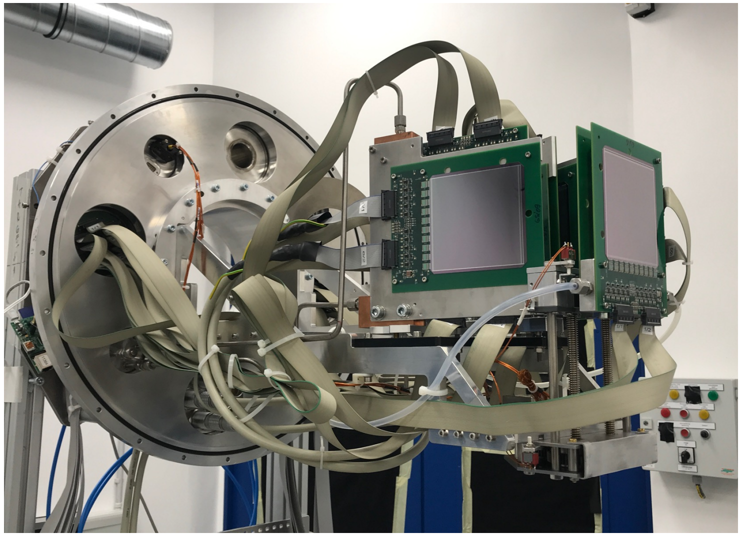


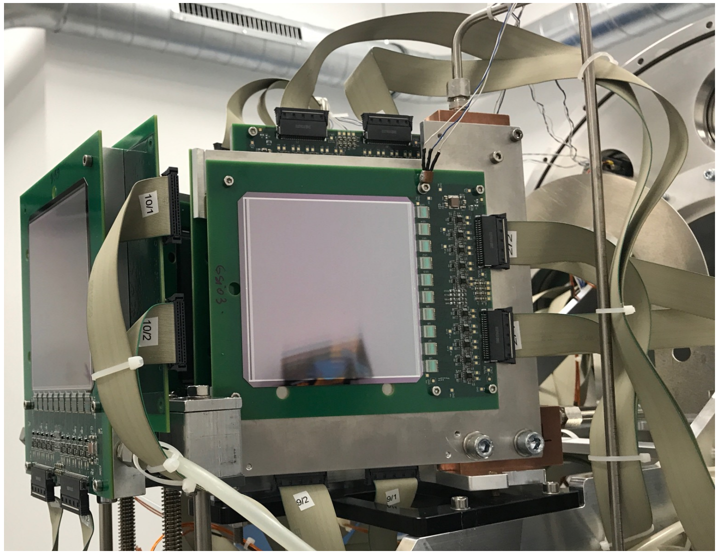
"Coctail beams" allow for better use of the available beam intensity. Advantage at 1 GeV/u: fully-stripped ions

Many outgoing fragments: identification is crucial for complete-kinematics experiments.

Example from S509 in 2022

FOOT: Tracking of beam and reaction products

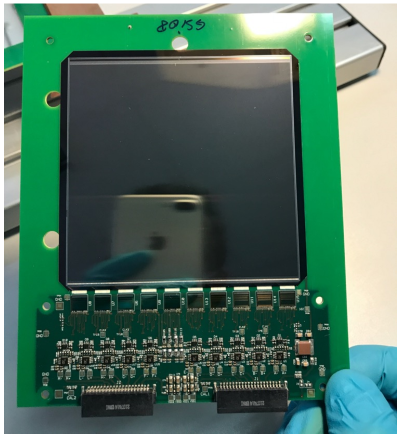


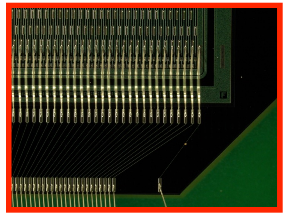


- **HAMAMATSU single-sided sensors, 150 µm thick.**
- **Active area 96 x 96 cm².**
- **Number of readout channels: 640 per detector.**
- **Rates up to 10 kHz.**
- **Water cooling.**

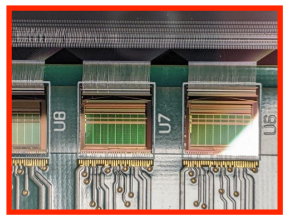
FOOT: FragmentatiOn Of Target

Two-arm FOOT configuration in 2022



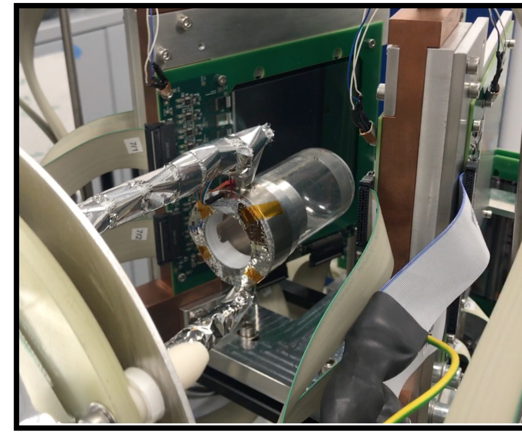


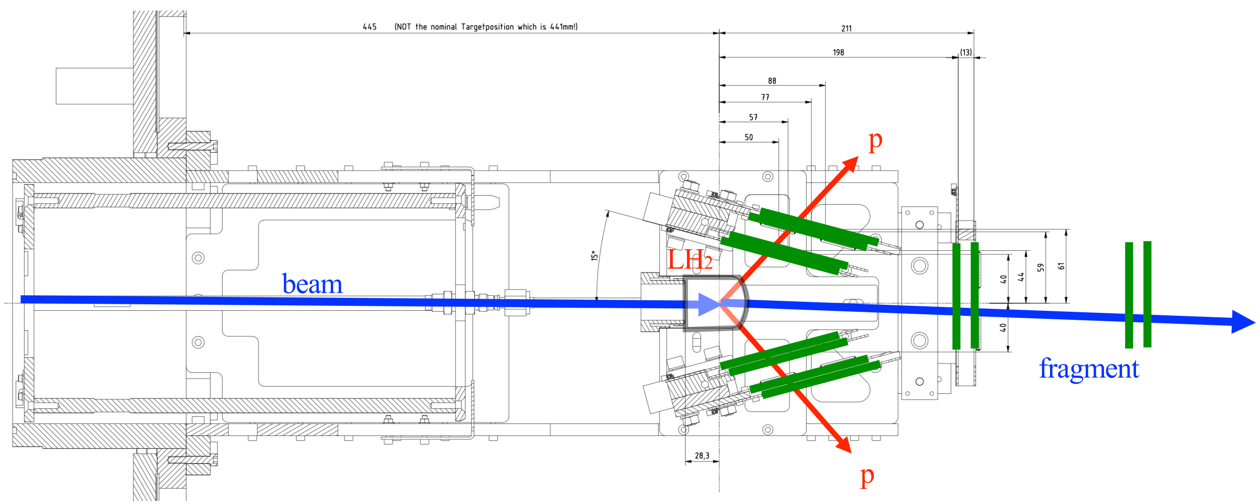
Strip pitch:
50 µm
Readout pitch:
150 µm



10 charge-sensitive ASICs from IDEAS, Norway

50 mm LH_2 target



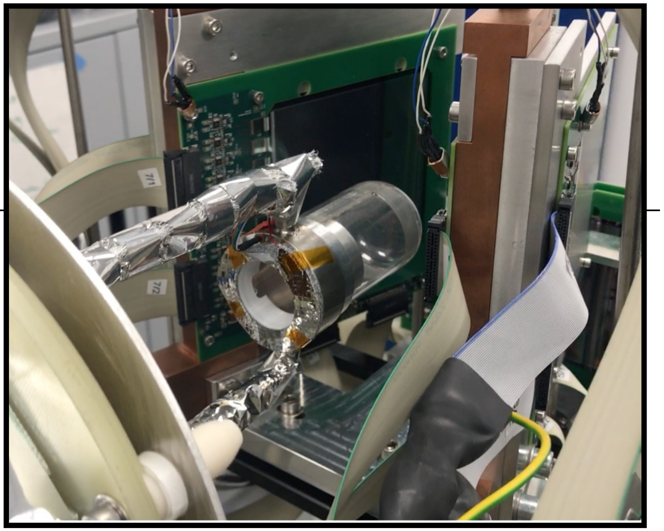


From R3BRoot simulations by A. Revel

Acc. (p,2p)	20%
Res. Theta	2mrad
Res. Vertex_Z	0,17mm
Res. MissM (p,2p)	4,5MeV
Acc. (p,2pn) t,u>0.5GeV/c2	35%
Res. MissP (p,2pn)	3,8MeV

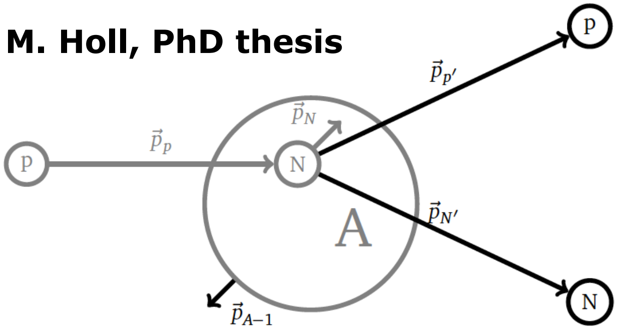
Engineering by: D. Körper, S. Utz, E. Casarejos

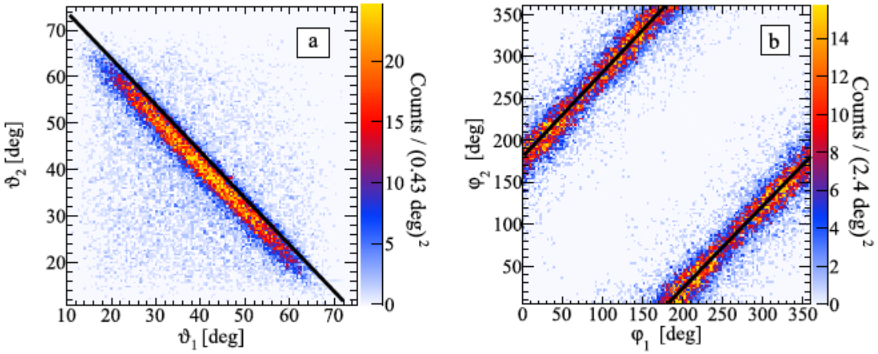
Quasi-free scatting



Quasi-free scattering is in many ways the "work horse" reaction of R³B and many other labs. => LH_2 target

M. Holl, PhD thesis

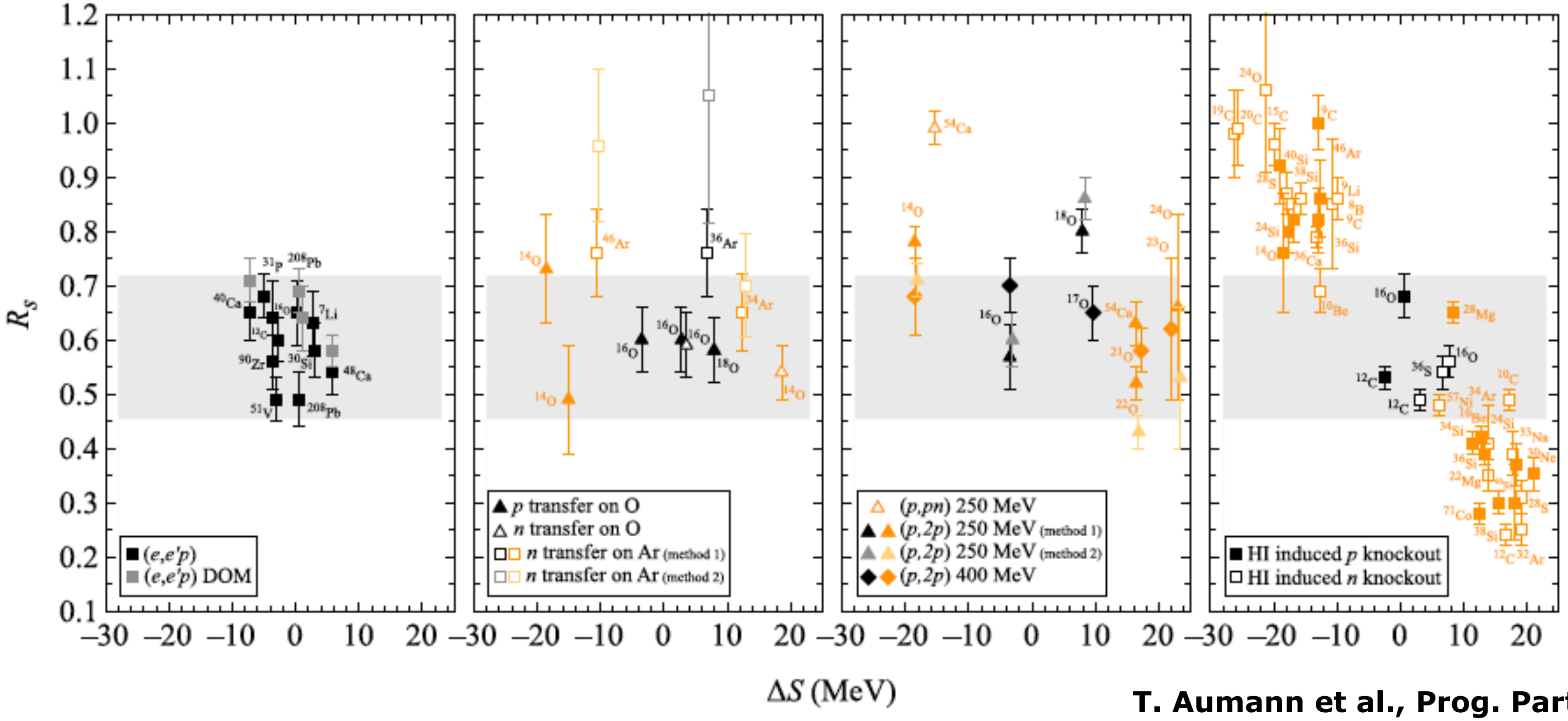




Idea:
Remove, selectively, one nucleon.
Obtain, e.g. spectroscopic factors; populate a well-defined state.
Ensure that multiple scattering is limited -> measure at minium of nn cross section.

V. Panin et al., PLB 753, 204 (2016)

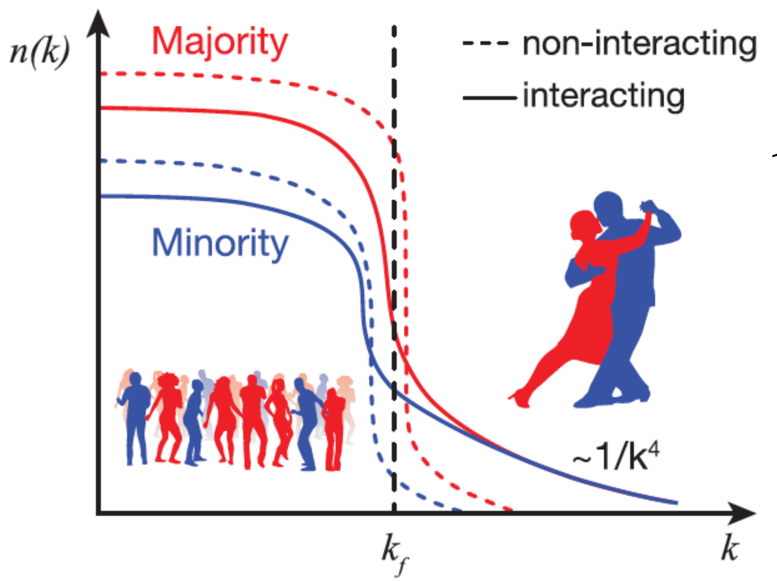
Quenching of single-particle strength



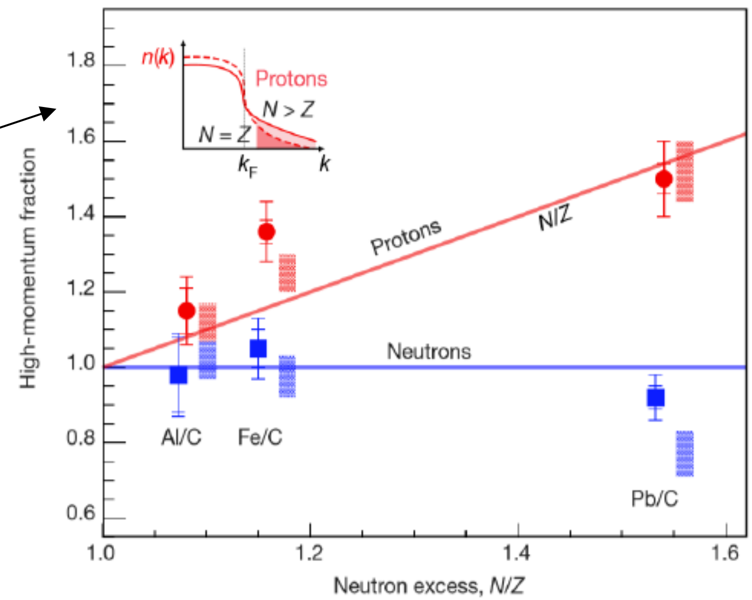
T. Aumann et al., Prog. Part. Nucl. Phys. 118, 103847 (2021)

Example for oxygen isotopes.
Direct reactions and quasi-free scattering, (p,2p) or (p,pn), show consistently no (or a weak) dependence on the difference of p and n separation energies – in contrast to (inclusive) reactions with HI targets at intermediate energies.

Short-range correlations



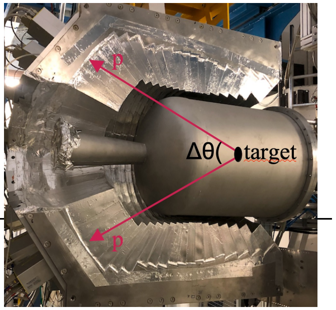
O. Hen et al., Science 346, 614 (2014)



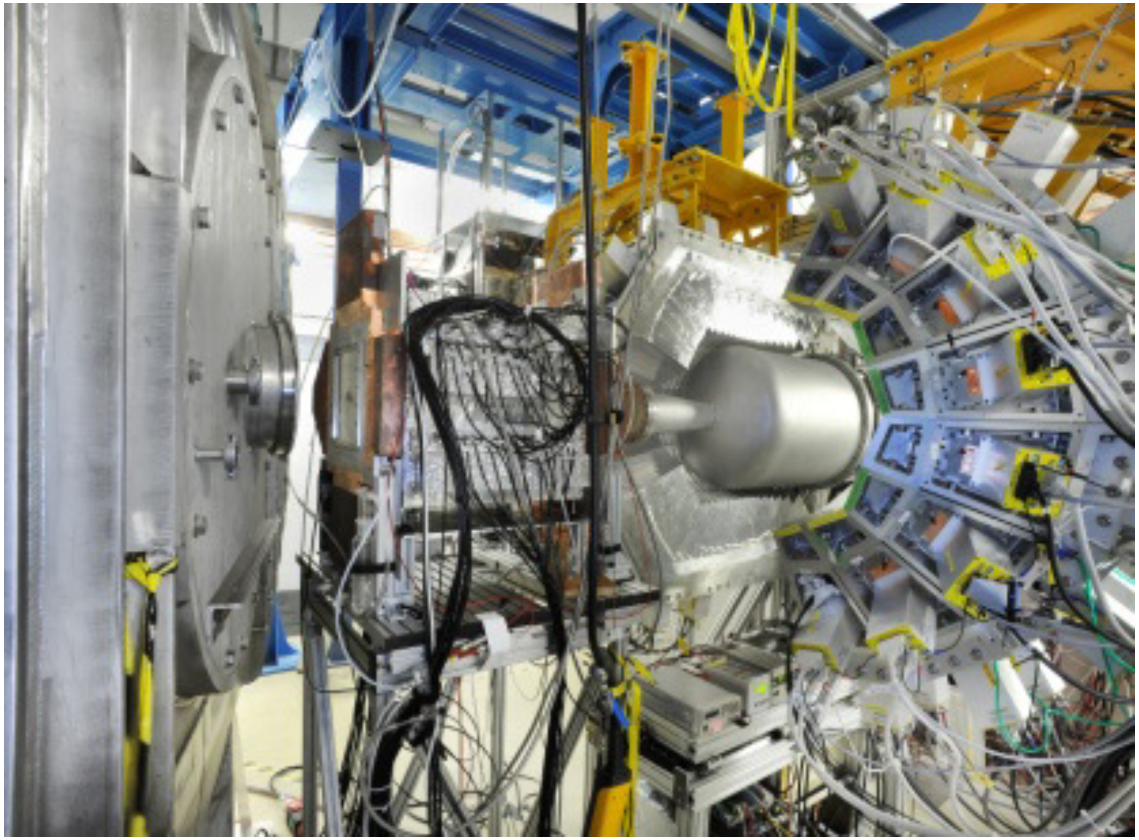
M. Duer et al., Nature 560, 617 (2018)

Short-range correlations can be probed using (p,2pp), (p,2pn) reactions over a larger range of isospin.

CALIFA - calorimeter

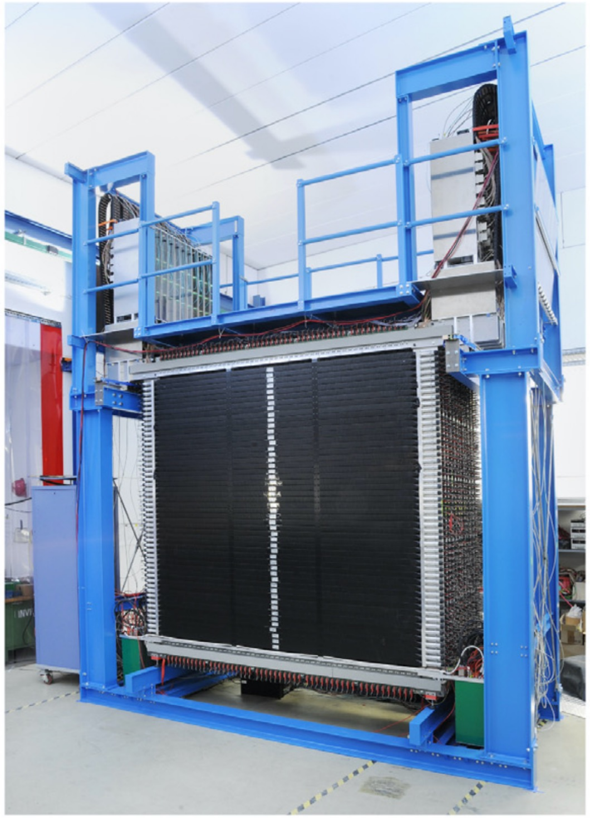


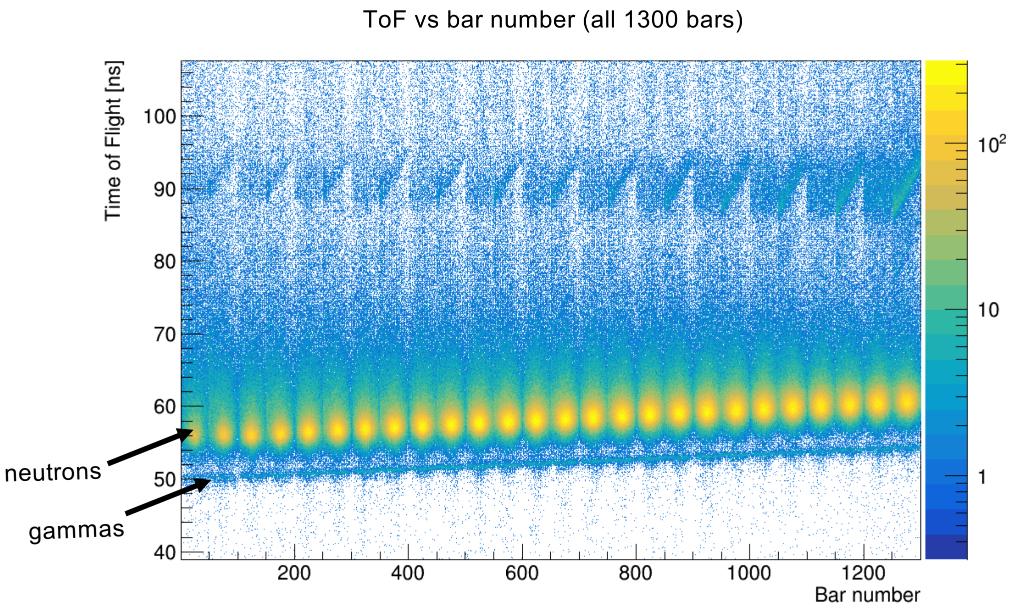
~2500 scintillator crystals (CsI) with APD readout



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

NeuLAND (2022)





Courtesy of Igor Gasparic

13 double planes with 2 x 50 scintillator bars, each

Able to reconstruct 4-momenta of multiple neutron hits

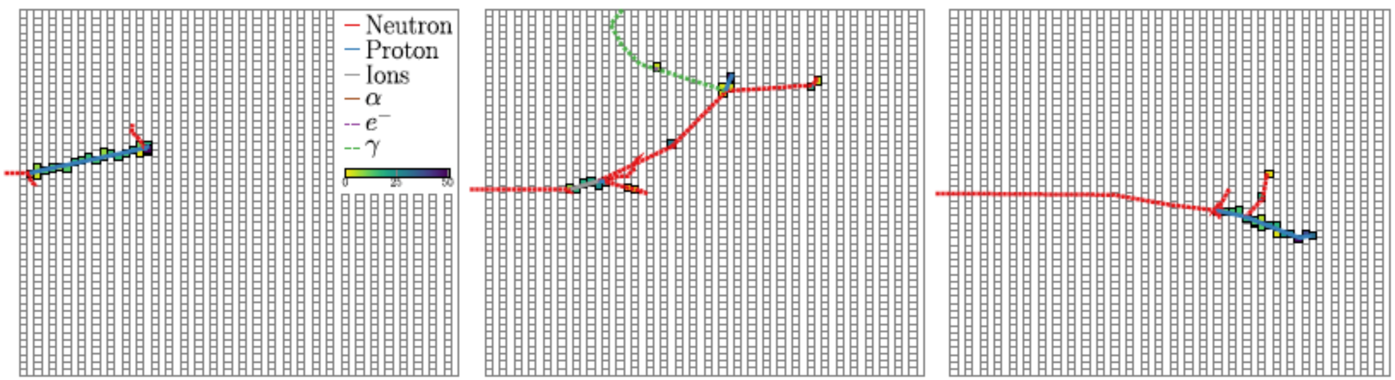
Detecting relativistic neutrons

QGSP_INCLXX_HP

	Reaction products	[%]
1	$n+n+p+d+\alpha+\alpha$	7.7
2	$n+n+n+p+p+\alpha+\alpha$	6.7
3	$n+p+{}^{11}\mathrm{B}$	4.9
4	$n+n+{}^{11}\mathrm{C}$	4.4
5	$n+n+n+p+p+d+d+\alpha$	2.7
6	$n+\alpha+\alpha+\alpha$	2.3
7	$n+p+\alpha+{}^{7}\mathrm{Li}$	2.2
8	$n+n+p+\alpha+{}^{6}Li$	2.0
9	$n+n+p+{}^{10}\mathrm{B}$	1.8
10	$n+n+n+n+p+p+p+d+\alpha$	1.8

QGSP_BERT_HP

	Reaction products	[%]
1	$n+p+{}^{11}\mathrm{B}$	9.8
2	$n+n+n+p+p+\alpha+\alpha$	9.1
3	$n+n+{}^{11}\mathrm{C}$	7.8
4	$n+n+p+{}^{10}\mathrm{B}$	4.1
5	$n+n+p+d+\alpha+\alpha$	4.0
6	$n+\alpha+\alpha+\alpha$	3.3
7	$n+p+{}^{11}\mathrm{C}+\pi^{-}$	2.6
8	$n+n+p+p+p+\alpha+\alpha+\pi^{-}$	2.1
9	$n+{}^{12}\mathrm{C}$	1.7
10	$n+n+n+n+p+p+p+d+\alpha$	1.4



K. Boretzky et al., NIM A1014, 165705 (2021)

Many open reaction channels, typcially not all energy is deposited in the first interaction => measure neutron ToF, deposited energy and all hits within the volume to extract the neutron multiplicty.

Nature 606, 678–682 (2022)

Observation of a correlated free four-neutron system

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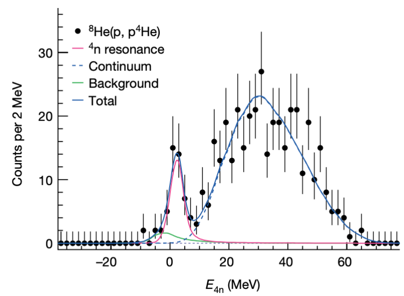
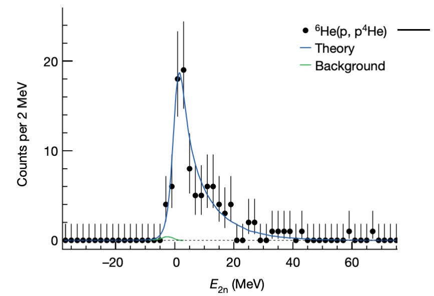
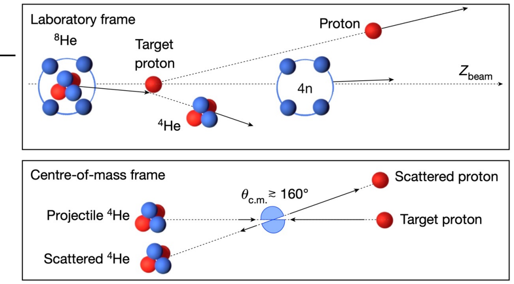
M. Duer[1✉], T. Aumann[1,2,3], R. Gernhäuser[4], V. Panin[2,5], S. Paschalis[1,6], D. M. Rossi[1], N. L. Achouri[7], D. Ahn[5,16], H. Baba[5], C. A. Bertulani[8], M. Böhmer[4], K. Boretzky[2], C. Caesar[1,2,5], N. Chiga[5], A. Corsi[9], D. Cortina-Gil[10], C. A. Douma[11], F. Dufter[4], Z. Elekes[12], J. Feng[13], B. Fernández-Domínguez[10], U. Forsberg[6], N. Fukuda[5], I. Gasparic[1,5,14], Z. Ge[5], J. M. Gheller[9], J. Gibelin[7], A. Gillibert[9], K. I. Hahn[15,16], Z. Halász[12], M. N. Harakeh[11], A. Hirayama[17], M. Holl[1], N. Inabe[5], T. Isobe[5], J. Kahlbow[1], N. Kalantar-Nayestanaki[11], D. Kim[16], S. Kim[1,16], T. Kobayashi[18], Y. Kondo[17], D. Körper[2], P. Koseoglou[1], Y. Kubota[5], I. Kuti[12], P. J. Li[19], C. Lehr[1], S. Lindberg[20], Y. Liu[13], F. M. Marqués[7], S. Masuoka[21], M. Matsumoto[17], J. Mayer[22], K. Miki[1,18], B. Monteagudo[7], T. Nakamura[17], T. Nilsson[20], A. Obertelli[1,9], N. A. Orr[7], H. Otsu[5], S. Y. Park[15,16], M. Parlog[7], P. M. Potlog[23], S. Reichert[4], A. Revel[7,9,24], A. T. Saito[17], M. Sasano[5], H. Scheit[1], F. Schindler[1], S. Shimoura[21], H. Simon[2], L. Stuhl[16,21], H. Suzuki[5], D. Symochko[1], H. Takeda[5], J. Tanaka[1,5], Y. Togano[17], T. Tomai[17], H. T. Törnqvist[1,2], J. Tscheuschner[1], T. Uesaka[5], V. Wagner[1], H. Yamada[17], B. Yang[13], L. Yang[21], Z. H. Yang[5], M. Yasuda[17], K. Yoneda[5], L. Zanetti[1], J. Zenihiro[5,25] & M. V. Zhukov[20]

$$E_r = 2.37 \pm 0.38(\text{stat.}) \pm 0.44(\text{sys.})\ \text{MeV},$$
$$\Gamma = 1.75 \pm 0.22(\text{stat.}) \pm 0.30(\text{sys.})\ \text{MeV}.$$





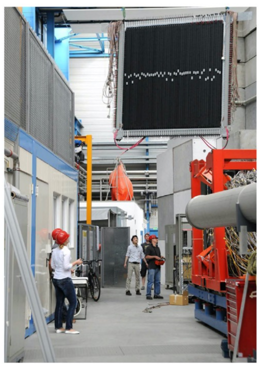


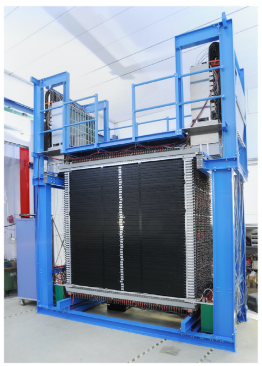
- Studying 4n system at SAMURAI in RIKEN
  - With NeuLAND demonstrator (only 4 double planes)
  - 4n detection efficiency < 1%
  - Indirect observation through missing-mass measurements
- Possibility to study 4n at R3B using full NeuLAND
  - 4n efficiency > 30% with 13 DP (>70% with 30 DP)
  - Direct observation of 4n is possible combining invariant-mass and missing-mass measurements

Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

NeuLAND: The high-resolution neutron time-of-flight spectrometer for R^3B at FAIR

K. Boretzky[a,*], I. Gašparić[b,c,a], M. Heil[a], J. Mayer[d], A. Heinz[e], C. Caesar[a,c], D. Kresan[a,c], H. Simon[a], H.T. Törnqvist[c], D. Körper[a], G. Alkhazov[f], L. Atar[a], T. Aumann[c,a,g], D. Bemmerer[h], S.V. Bondarev[f], L.T. Bott[i], S. Chakraborty[j], M.I. Cherciu[k], L.V. Chulkov[l], M. Ciobanu[k], U. Datta[j], E. De Filippo[m], C.A. Douma[n], J. Dreyer[h], Z. Elekes[o], J. Enders[c,g], D. Galaviz[p,q], E. Geraci[r,m], B. Gnoffo[r,m], K. Göbel[i], V.L. Golovtsov[f], D. Gonzalez Diaz[c,s], N. Gruzinsky[f], T. Heftrich[i], H. Heggen[a], J. Hehner[a], T. Hensel[h,t], E. Hoemann[d], M. Holl[e], A. Horvat[c], Á. Horváth[u], G. Ickert[a], D. Jelavić Malenica[c,b], H.T. Johansson[e], B. Jonson[e], J. Kahlbow[c], N. Kalantar-Nayestanaki[n,1], A. Kelić-Heil[a], M. Kempe[h,2], K. Koch[a], N.G. Kozlenko[f], A.G. Krivshich[f], N. Kurz[a], V. Kuznetsov[f], C. Langer[v,a], Y. Leifels[a], I. Lihtar[b], B. Löher[a], J. Machado[w], N.S. Martorana[r,x], K. Miki[c], T. Nilsson[e], E.M. Orischin[f,2], E.V. Pagano[x], S. Pirrone[m], G. Politi[r,m], P.- M. Potlog[k], A. Rahaman[j], R. Reifarth[i,g], C. Rigollet[n], M. Röder[t], D.M. Rossi[c], P. Russotto[x], D. Savran[a], H. Scheit[c], F. Schindler[c], D. Stach[h], E. Stan[k], J. Stomvall Gill[e], P. Teubig[q], M. Trimarchi[m,y], L. Uvarov[f], M. Volknandt[i], S. Volkov[f], A. Wagner[h], V. Wagner[c], S. Wranne[e], D. Yakorev[h], L. Zanetti[c], A. Zilges[d], K. Zuber[t], for the R^3B collaboration





4n detection efficiencies with 12 double-planes

200 MeV		generated 1	2	3	4	5
detected	0	41	16	6	2	
	1	**51**	39	22	11	
	2	8	**33**	34	25	
	3	0	11	**28**	32	
	4	0	0	10	**31**	

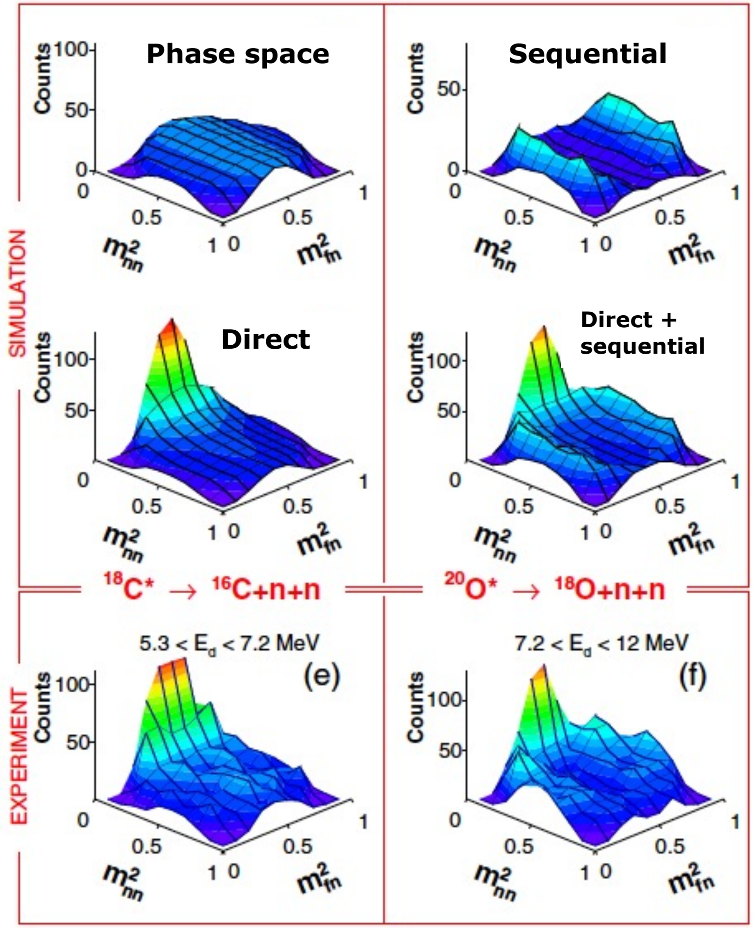
4n detection efficiencies with 30 double-planes

200 MeV		Generated 1	2	3	4
detected	0	7	0	0	0
	1	**90**	28	5	1
	2	3	**58**	24	5
	3	0	13	**48**	22
	4	0	0	23	**72**

N-n correlations

Use (p,2p) reactions to remove deeply bound protons. As a result 2 neutrons can end up in the continuum.

Study the 2 neutron decay: are there correlations?



A. Revel et al., Phys. Rev. Lett. 120, 152504 (2018)

The R³B setup in Phase-0*

S444 Detection system commissioning

S467 Single-particle structure of Ca isotopes

Test runs with proton and ^{208}Pb beams

S455 Fission studies @R3B (next talk by Jose Benlliure)

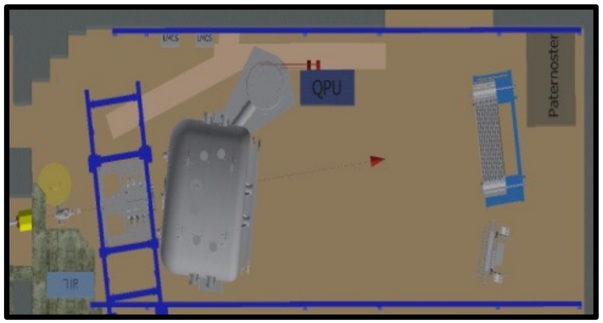
S515 Constraining energy-density functionals and the density-dependence of the symmetry energy

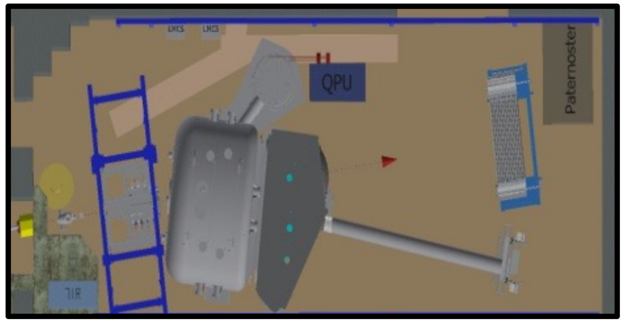
S494 Coulomb dissociation of ^{16}O into ^{12}C and ^{4}He.

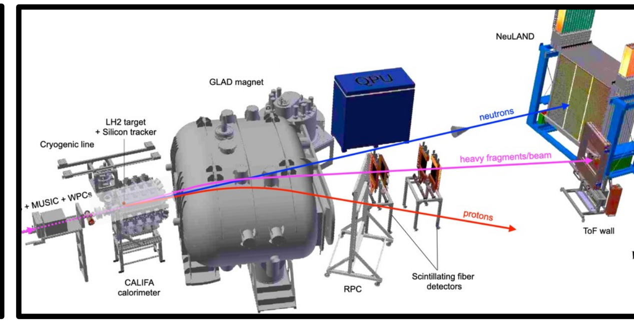
Test run with ^{12}C beam

S522 First characterization of Short-Range Correlations in exotic nuclei

S509 Study of multi-neutron correlations in drip-line nuclei.







2020 | 2021 | 2022

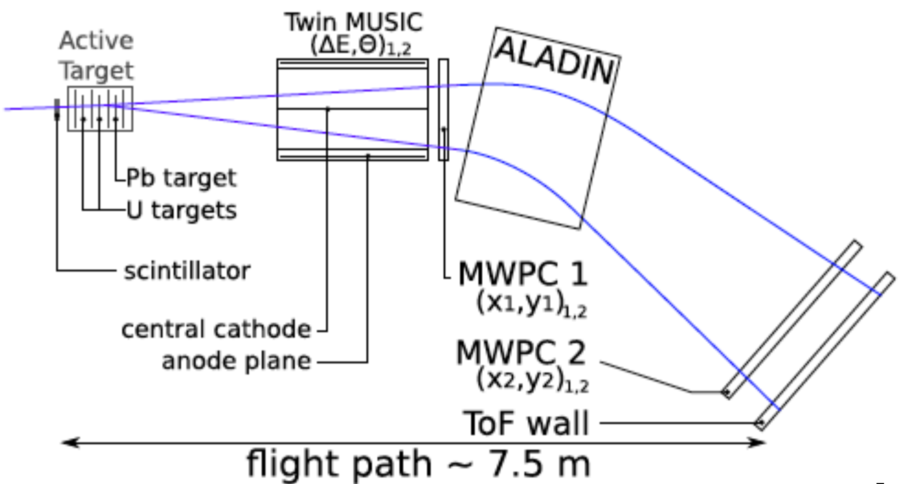
- CALIFA Barrel
- NeuLAND 8 double-planes
- SOFIA tracking detectors
- R3BMusic
- Solid targets (CH2, Pb, C)

- CALIFA iPHOS
- NeuLAND 12 double-planes
- New fiber detectors
- AMS silicon trackers
- 15 mm LH2 target, solid targets

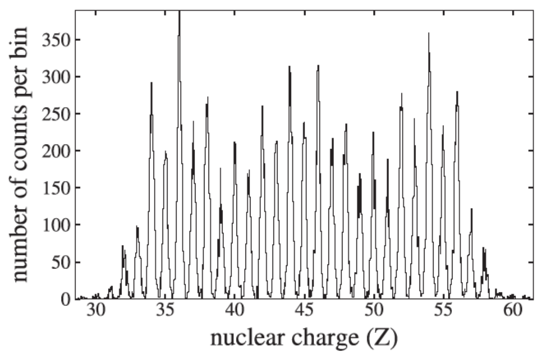
- Neuland 13 double planes
- RPC behind GLAD
- New FOOT silicon trackers
- 50 mm LH2 target

*** Phase-0 refers to experiments using FAIR detector systems but a the GSI accelerator facility**

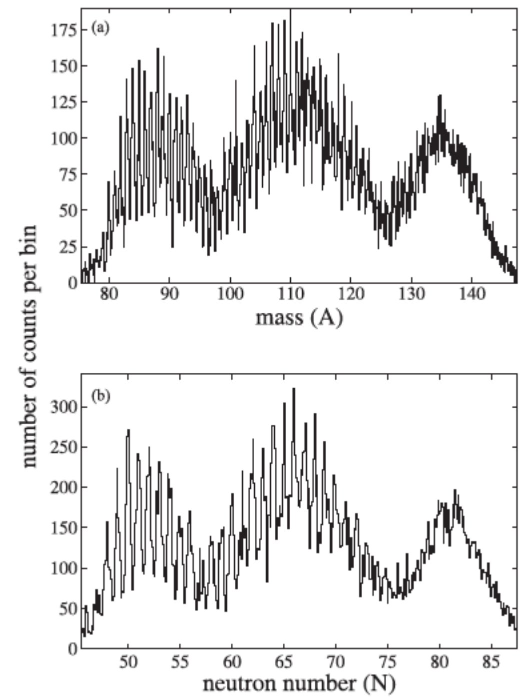
SOFIA* – Fission studies at R^3B



Fission in inverse kinematics is induced by e.m interaction with a U (Pb) target or with (p,2pf) using the LH_2 target.



Examples for fission of ^{226}Th. A and Z of both fission fragments are measured in coincidence.



A. Chatillon et al., B. Phys. Rev. C 99, C. 054628 (2019)

***Studies On Fission with ALADIN**

Conclusions

- **R³B investigates reactions of unstable beams at relativistic energies in complete kinematics.**
- **This requires separated radioactive beams from the FRS or Super-FRS.**
- **The setup is very versatile.**
- **A broad physics program includes studies of the evolution of nuclear shell structure, short-range correlations, nuclear fission ….**
- **A unique set of detectors allows for those studies.**
- **High secondary beam energies are often mandatory.**