Direct Reactions with Exotic Beams at Low Momentum Transfer: Investigations with Stored Beams and with Active Targets

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II. Direct Reactions at Internal Targets of Storage Rings

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2. Recent Experiments and Future Perspectives

III. Direct Reactions with Active Targets

1. Experimental Concept
2. Small Angle Elastic Proton Scattering
   – a Tool to Study the Radial Shape of Exotic Nuclei

IV. Conclusions

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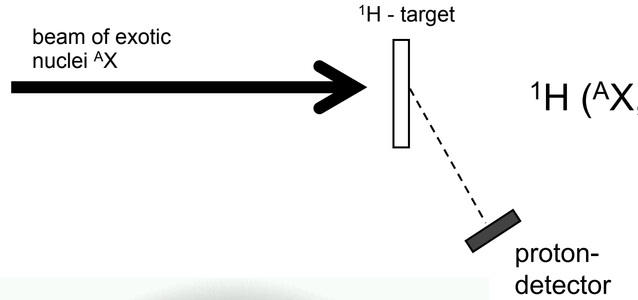
* **EXL**: **Ex**otic Nuclei Studied in **L**ight-Ion Induced Reactions at the NESR Storage Ring

I. Introduction: Direct Reactions with Radioactive Beams in Inverse Kinematics



$^{1}H\ (^{A}X,\ ^{1}H)\ ^{A}X$

classical method of nuclear spectroscopy:

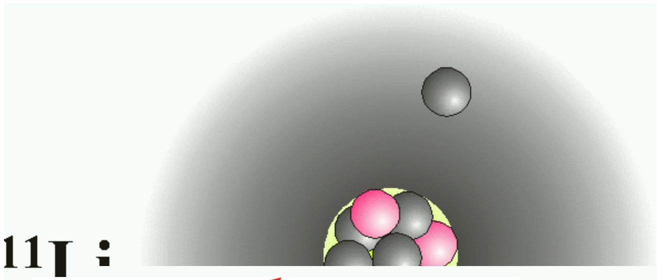
⇒ light ion induced direct reactions: (p,p), (p,p'), (d,p), ...

⇒ to investigate exotic nuclei: inverse kinematics

⇒ important information at low momentum transfer!

of particular interest:

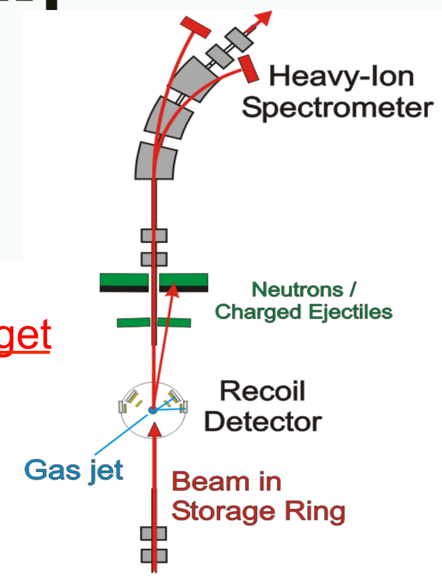
⇒ radial shape of nuclei: skin, halo structures
⇒ doubly magic nuclei: ^{56}Ni, ^{132}Ni
⇒ parameters of the EOS :
nuclear compressibility, symmetry energy



future perspectives at FAIR:
⇒ profit from intensity upgrade (up to 10^4 !!)
⇒ explore new regions of the chart of nuclides
⇒ use new and powerful methods:

EXL: direct reactions at internal storage ring target
⇒ high luminosity even for very low momentum transfer measurements

ACTAR: active Target at R^3B
⇒ access to very short life times: $T_{1/2} \leq 1$ sec



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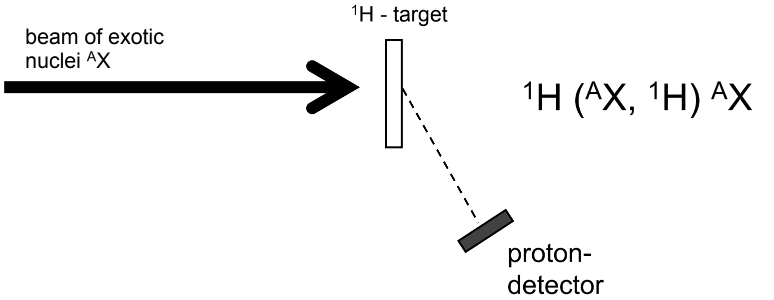

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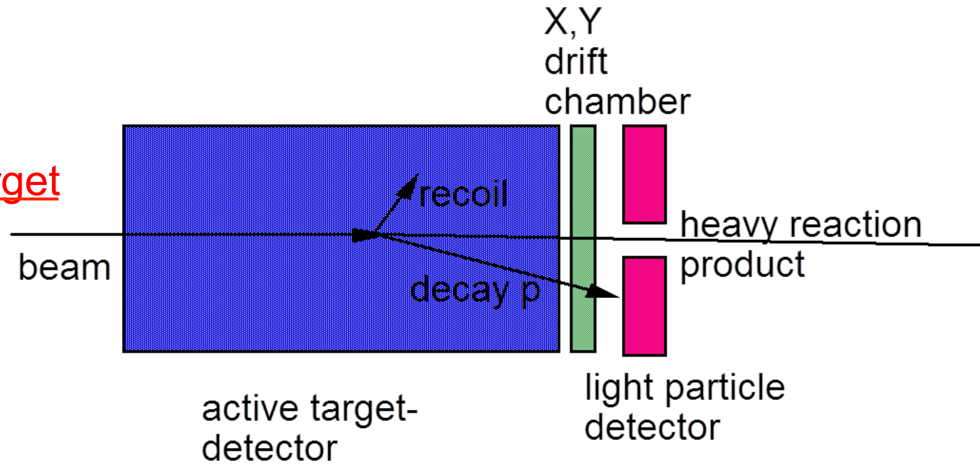
First Experiments already performed



Nuclear Physics with Radioactive Beams at the Present GSI Facility

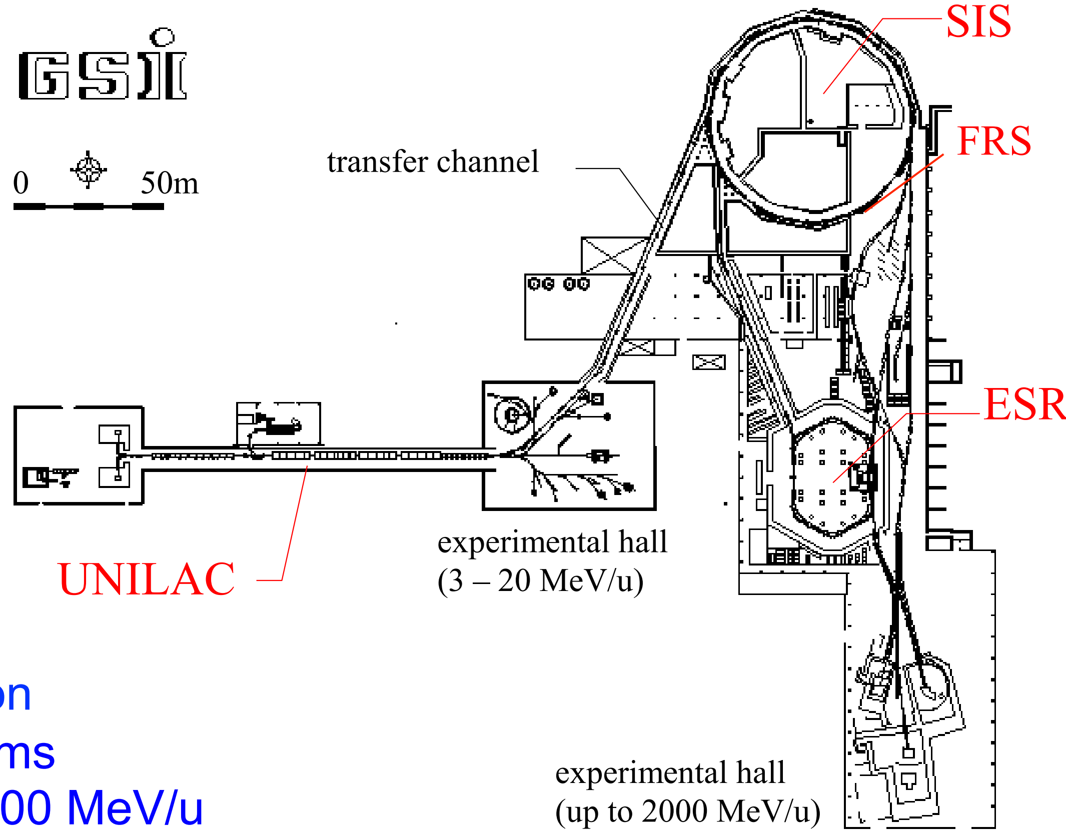
The Present GSI Accelerator Facilities:

UNILAC: universal linear accelerator
all ions (^{1}H ...^{238}U)
E = 3 - 20 MeV/u

SIS: heavy ion synchrotron
E = 100 - 2000 MeV/u

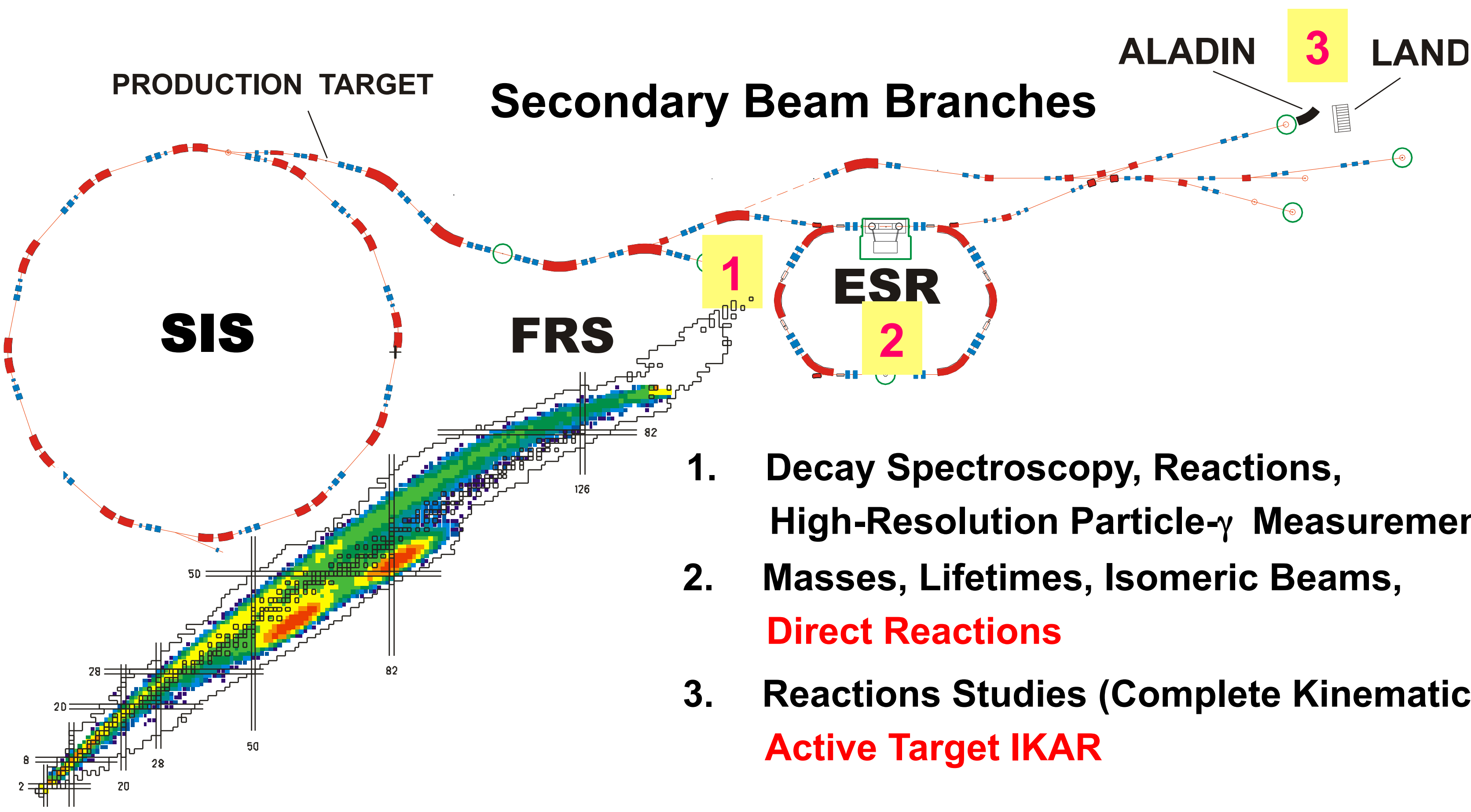
ESR: experimental storage ring
beam cooling
⇒ excellent beam qualities

FRS: fragment separator
projectile fragmentation, fission
⇒ secondary radioactive beams
with energies E ≥ 100 – 1000 MeV/u



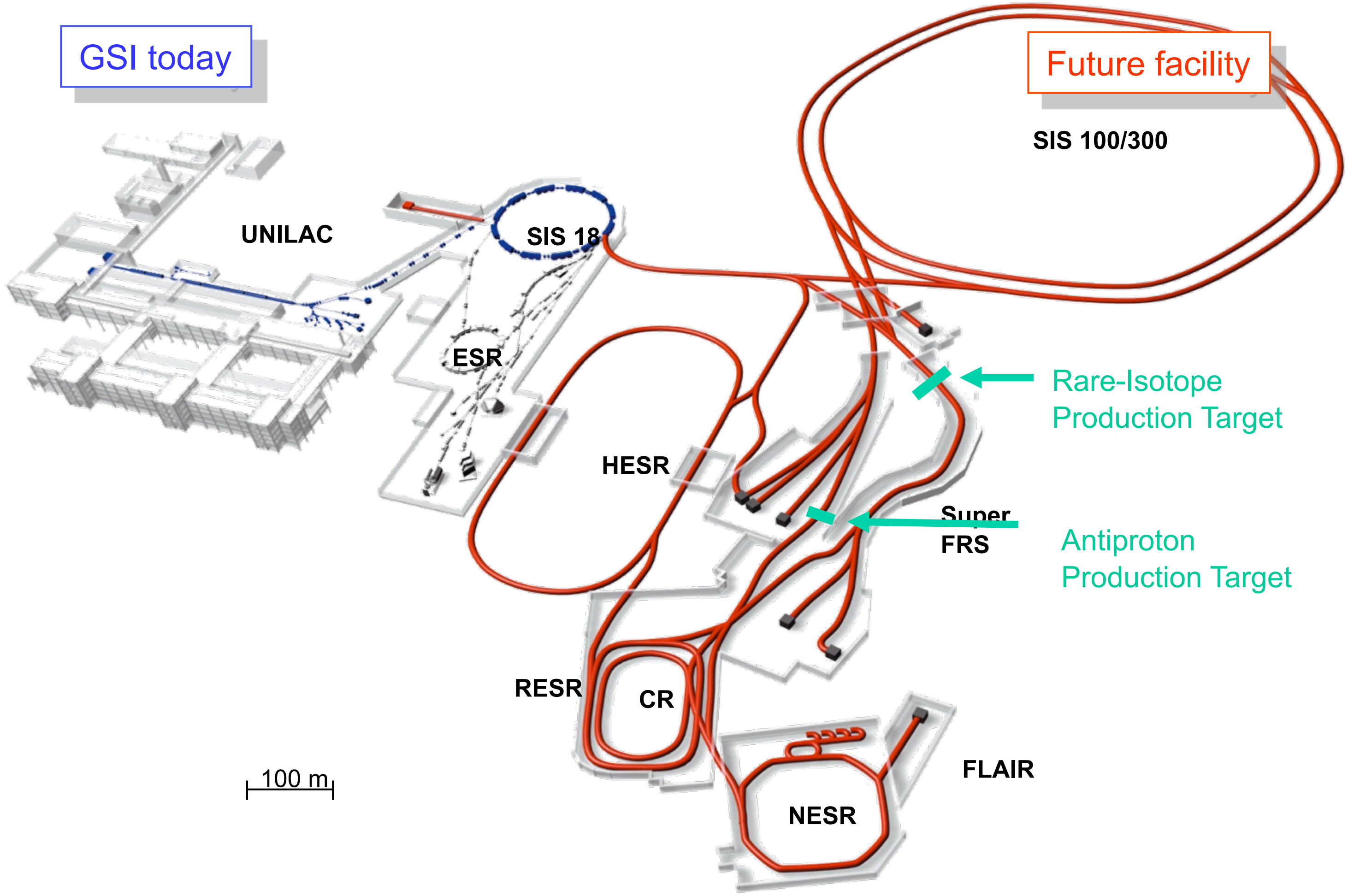
The Present Radioactive Beam Facility at GSI

FRS: In-Flight Separator & High-Resolution Spectrometer

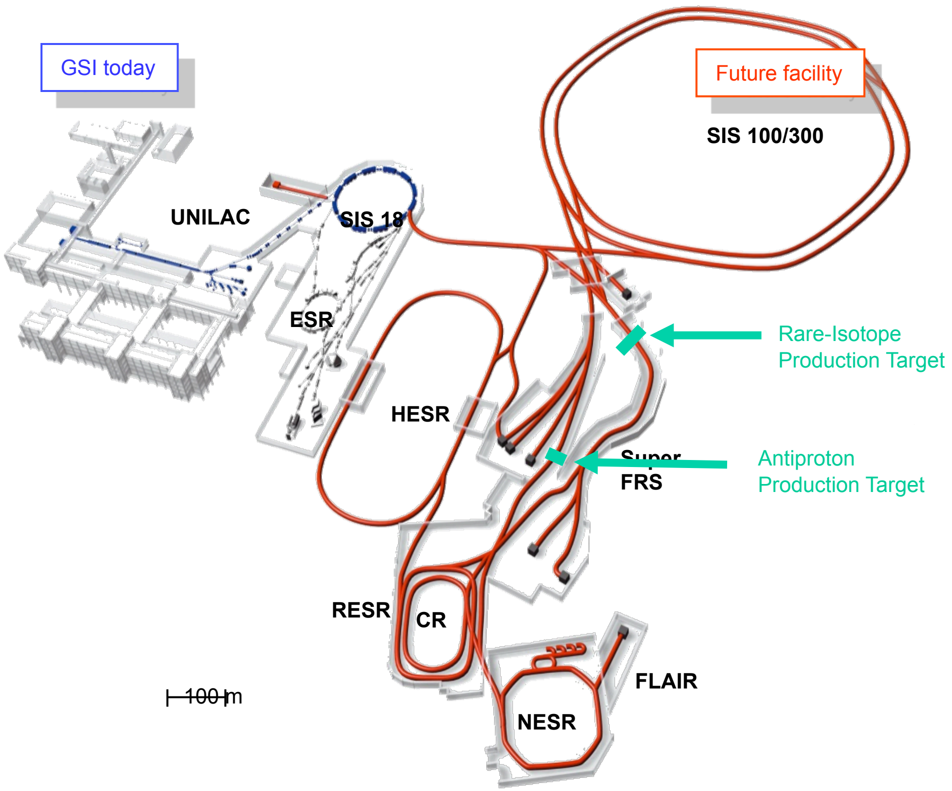


1. Decay Spectroscopy, Reactions,
   High-Resolution Particle-γ Measurements
2. Masses, Lifetimes, Isomeric Beams,
   Direct Reactions
3. Reactions Studies (Complete Kinematics)
   Active Target IKAR

FAIR: Facility for Antiproton and Ion Research



FAIR: Facility Characteristics



Primary Beams

- 10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- $2(4) \times 10^{13}$/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

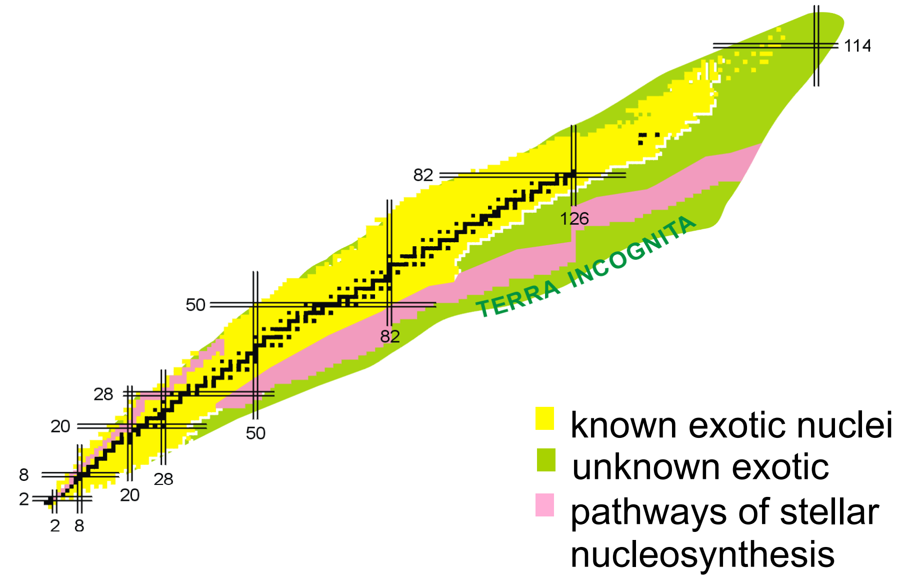
Storage and Cooler Rings

- 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

Nuclear Physics with Radioactive Beams - Physics Questions to be Adressed



regions of interest:

⇒ towards the driplines for medium heavy and heavy nuclei

physics interest:

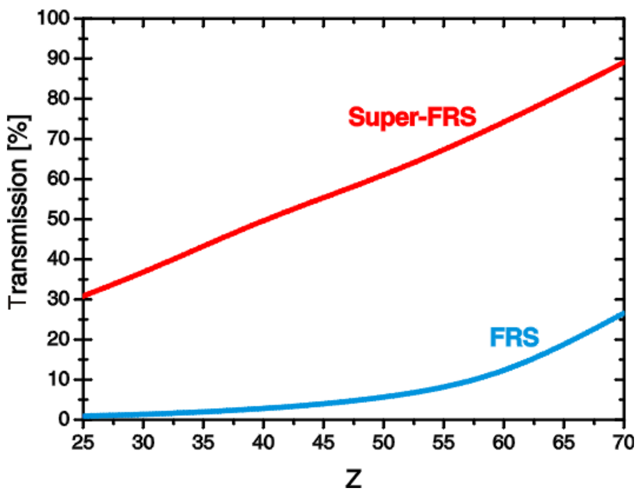
- matter distributions (halo, skin…)
- single-particle structure evolution (new magic numbers, new shell gaps, spetroscopic factors)
- NN correlations, pairing and clusterization phenomena
- new collective modes (different deformations for p and n, giant resonance strength)
- parameters of the nuclear equation of state
- in-medium interactions in asymetric and low-density matter
- astrophysical r and rp processes, understanding of supernovae

Light-Ion Induced Direct Reactions

- elastic scattering (p,p), (α,α), …
  nuclear matter distribution ρ(r), skins, halo structures
- inelastic scattering (p,p'), (α,α'), …
  giant resonances, deformation parameters, B(E2) values, transition densities
- charge exchange reactions (p,n), (^{3}He,t), (d, ^{2}He), …
  Gamow-Teller strength
- transfer reactions (p,d), (p,t), (p, ^{3}He), (d,p), …
  single particle structure, spectroscopic factors
  spectroscopy beyond the driplines
  neutron pair correlations
  neutron (proton) capture cross sections
- knock-out reactions (p,2p), (p,pn), (p,p ^{4}He)…
  ground state configurations, nucleon momentum distributions, cluster correlations

Nuclear Physics with Radioactive Beams at FAIR: NUSTAR: NUclear STructure, Astrophysics and Reactions

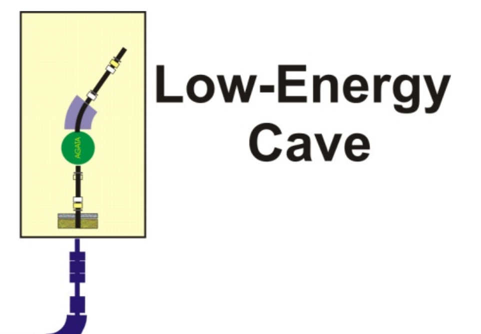
I High intensity primary beams from SIS 100 (e.g. 10^{12} ^{238}U / sec at 1 GeV/u)

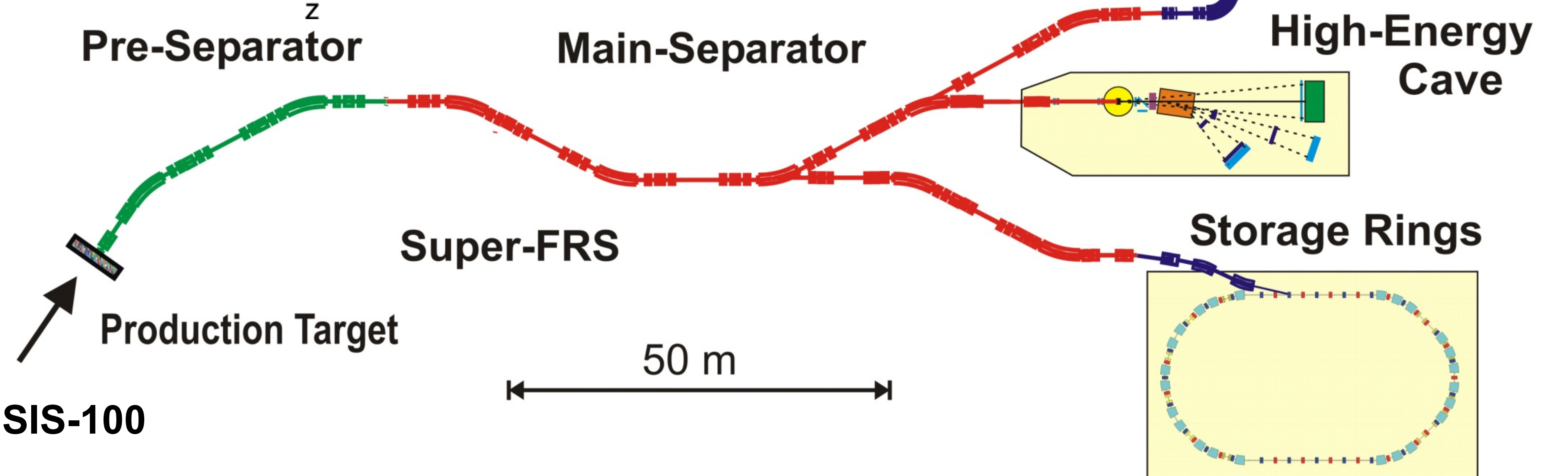


II Superconducting large acceptance Fragmentseparator

Optimized for efficient transport of fission products

III Three experimental areas



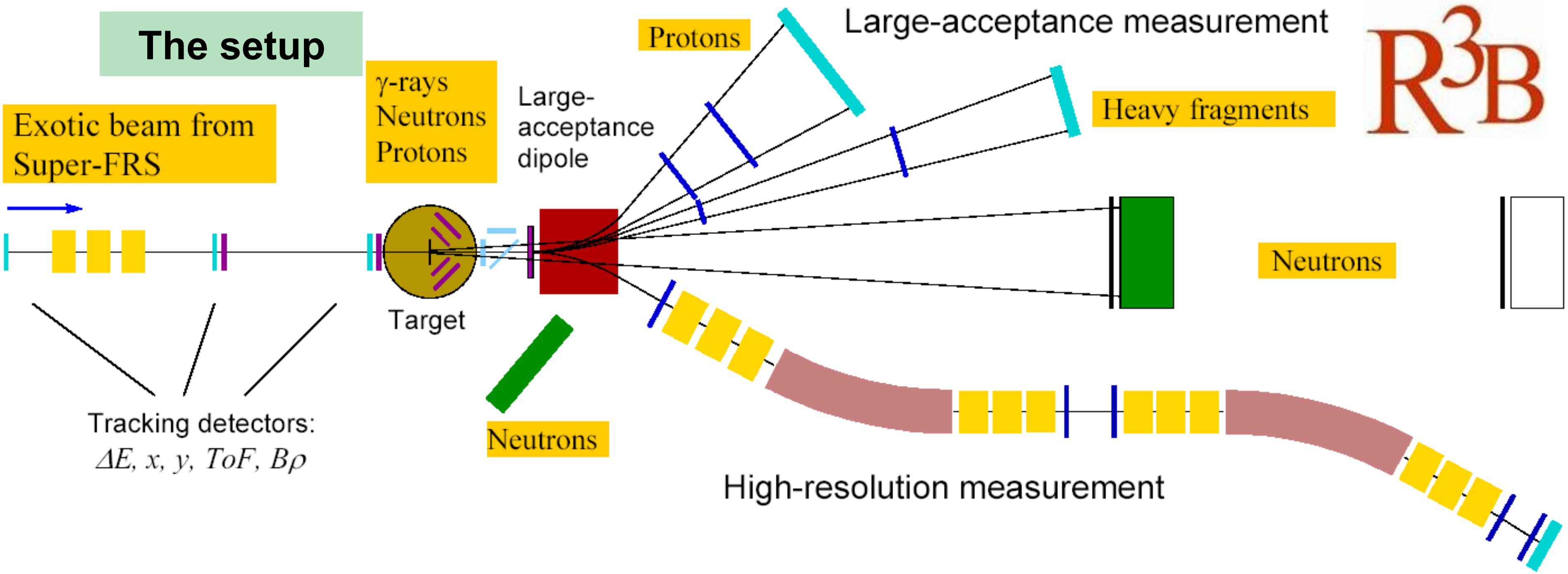


Reactions with Relativistic Radioactive Beams at FAIR

- R^3B: Reactions with Relativistic Radioactive Beams
  ⇒ High Energy Branch
- EXL: EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring
  ⇒ Ring Branch
- ELISe: ELectron Ion Scattering in a Storage Ring e-A Collider
  ⇒ Ring Branch

R3B: Reactions with Relativistic Radioactive Beams

The setup

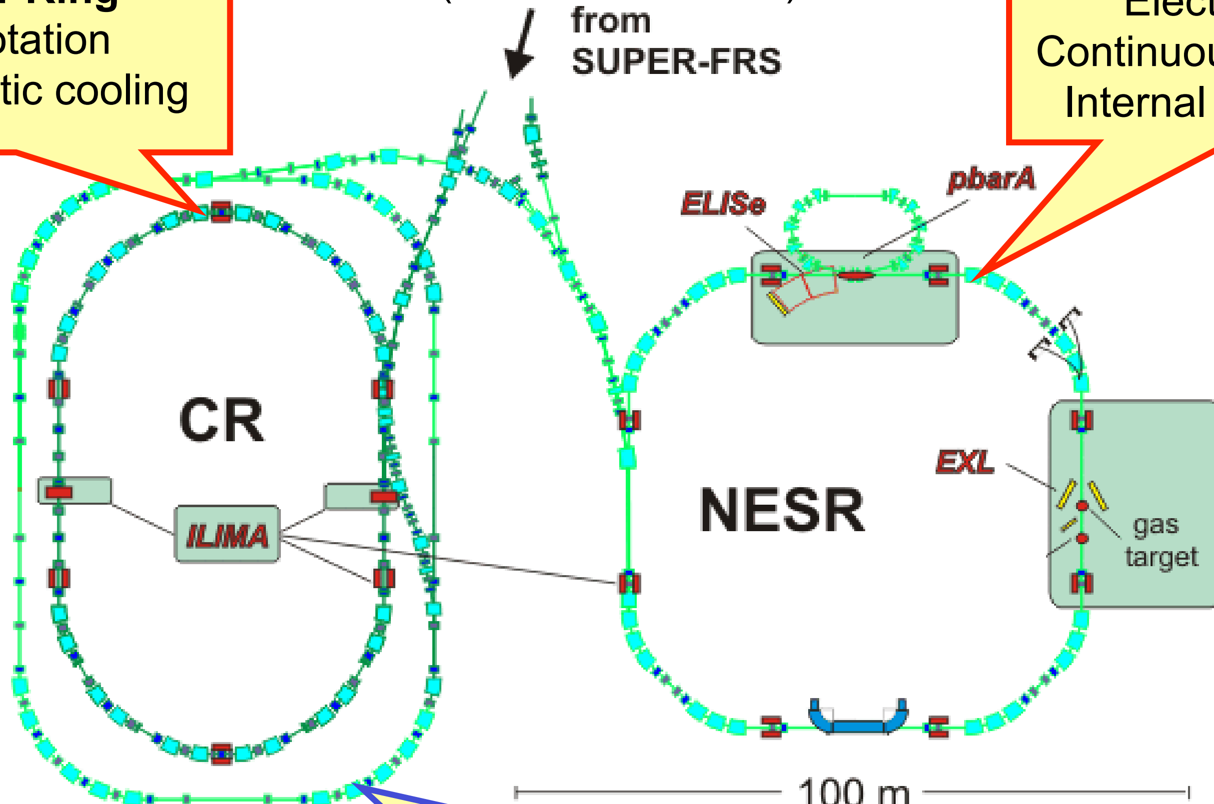


<u>The R³B experiment:</u> a universal setup for kinematical complete measurements

II. Direct Reactions at Internal Targets of Storage Rings

Collector Ring
Bunch rotation
Fast stochastic cooling

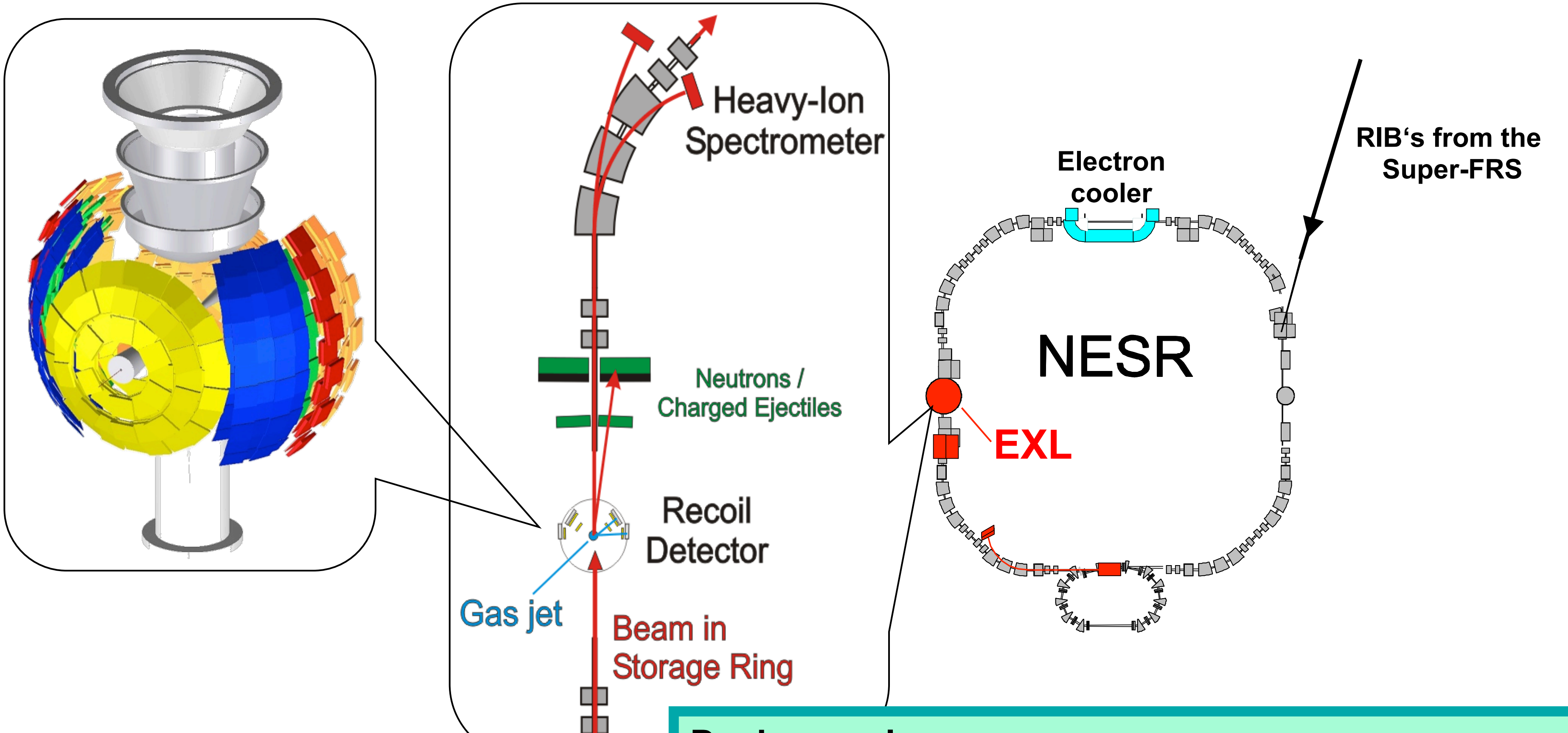
RIB
(740 MeV/nucleon)



NESR
Electron cooling
Continuous accumulation
Internal gas jet targets

RESR
Deceleration (1T/s) to 100 - 400 MeV/nucleon

The EXL Project: EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring



Detection systems for:

- Target recoils and gammas (p,α,n,γ)
- Forward ejectiles (p,n)
- Beam-like heavy ions

Design goals:

- Universality: applicable to a wide class of reactions
- High energy resolution and high angular resolution
- Large solid angle acceptance
- Specially dedicated for low q measurements with high luminosity (> 10^{29} cm^{-2} s^{-1})

Light-Ion Induced Direct Reactions at Low Momentum Transfer

- elastic scattering (p,p), (α,α), …
  nuclear matter distribution ρ (r), skins, halo structures
- inelastic scattering (p,p'), (α,α'), …
  deformation parameters, B(E2) values, transition densities, giant resonances
- transfer reactions (p,d), (p,t), (p, ^{3}He), (d,p), …
  single particle structure, spectroscopic factors, spectroscopy beyond the driplines, neutron pair correlations, neutron (proton) capture cross sections
- charge exchange reactions (p,n), (^{3}He,t), (d, ^{2}He), …
  Gamow-Teller strength
- (knock-out reactions (p,2p), (p,pn), (p,p ^{4}He)…
  ground state configurations, nucleon momentum distributions)

for almost all cases:

region of low momentum transfer contains most important information

<u>Speciality of EXL:</u>

measurements at very low momentum transfer

$\Rightarrow$ complementary to R^{3}B !!!

Experiments to be Performed at Very Low Momentum Transfer – Some Selected Examples

- Investigation of Nuclear Matter Distributions:

  ⇒ halo, skin structure

  ⇒ probe in-medium interactions at extreme isospin (almost pure neutron matter)

  ⇒ in combination with electron scattering (ELISe project @ FAIR):
  separate neutron/proton content of nuclear matter (deduce neutron skins)

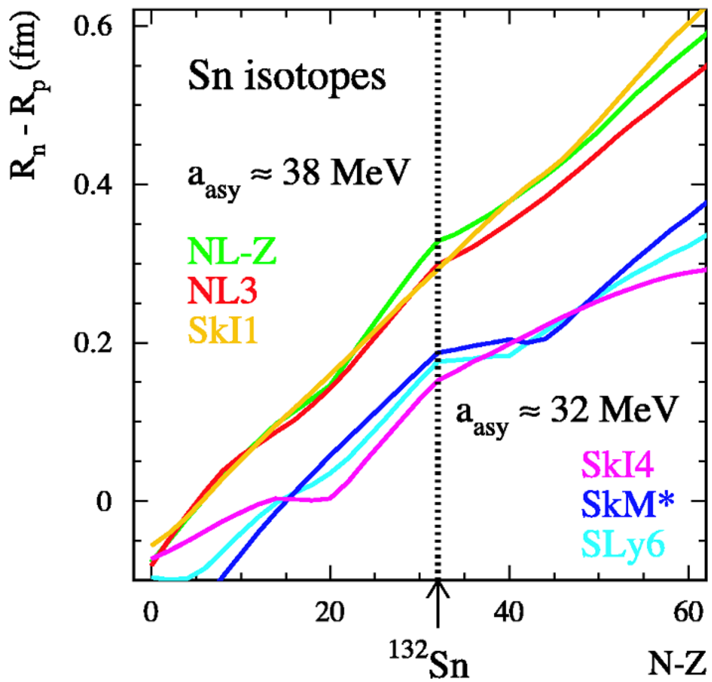
method: elastic proton scattering ⇒ at low q: high sensitivity to nuclear periphery

Proposed Experiments at FAIR

- investigation of nuclear matter distributions along isotopic chains towards proton/neutron asymmetric matter
- investigation of the same nuclei by (e,e) (ELISe) and (p,p) (EXL) scattering
  - ⇨ separate neutron/proton content of nuclear matter
  - ⇨ unambiguous and “model independent” determination of size and radial shape of neutron skins (halos)

example: Sn isotopes
at the nuclear surface:
almost pure neutron matter
⇨ probe isospin dependence of effective in-medium interactions
⇨ sensitivity to the asymmetry energy (volume and surface term!)

theoretical prediction: P.-G. Reinhard



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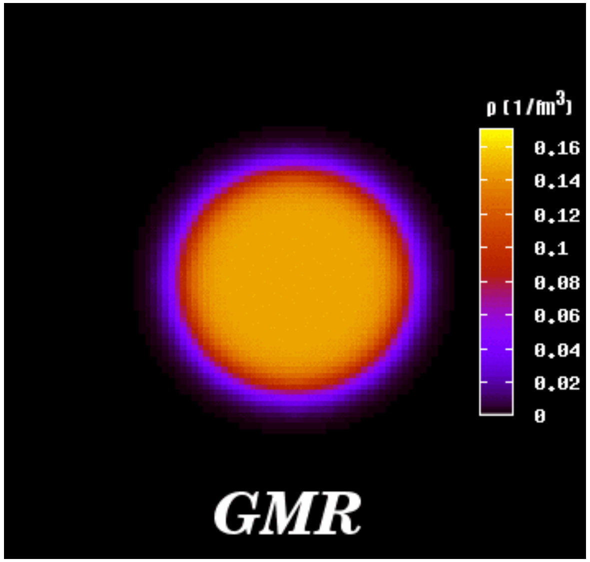
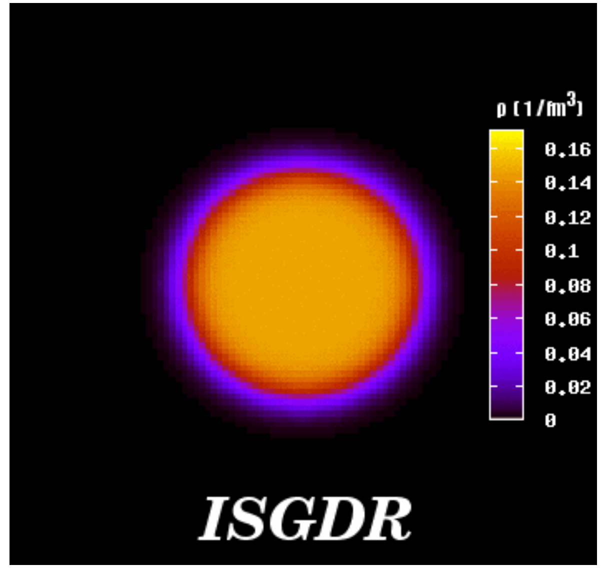
- Investigation of the Giant Monopole Resonance:
  - ⇒ gives access to nuclear compressibility ⇒ key parameters of the EOS
  - ⇒ new collective modes (breathing mode of neutron skin)

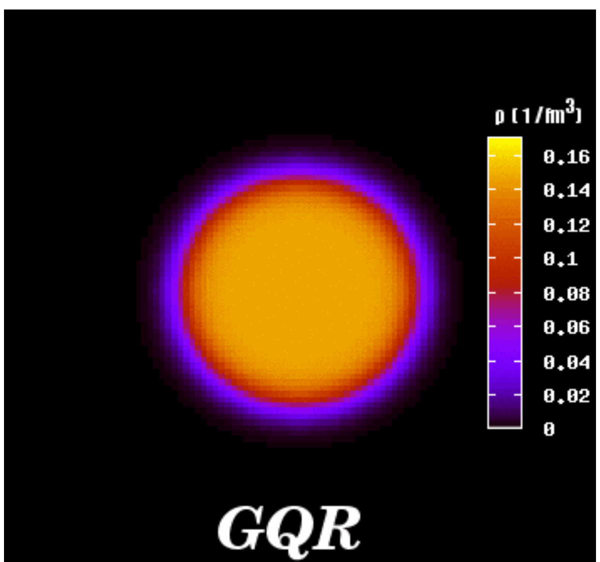
method: inelastic α scattering at low q

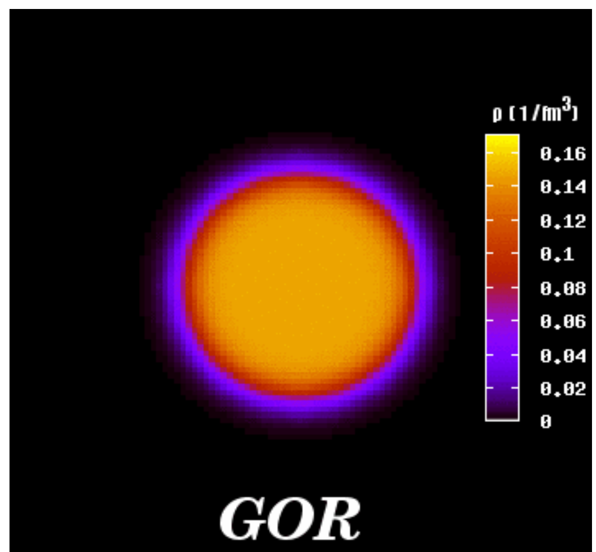
The Collective Response of the Nucleus: Giant Resonances





M. Itoh





Investigation of the Giant Monopole Resonance in Doubly Magic Nuclei by Inelastic α-Scattering

- GMR gives access to nuclear compressibility K_{nm} (Z,N) ~ $\rho_0^2 \, d^2(E/A) / d\rho^2 \,|_{\rho 0}$

  ⇨ key parameter of EOS

- investigation of isotopic chains arround ^{132}Sn, ^{56}Ni, … with high δ = (N-Z)/A

  ⇨ disentangle different contributions to

  $K_A = K_{vol} + K_{surf} A^{-1/3} + K_{sym} ((N-Z)/A)^2 + ...$

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  ⇒ gives access to nuclear compressibility ⇒ key parameters of the EOS

  ⇒ new collective modes (breathing mode of neutron skin)

method: inelastic α scattering at low q

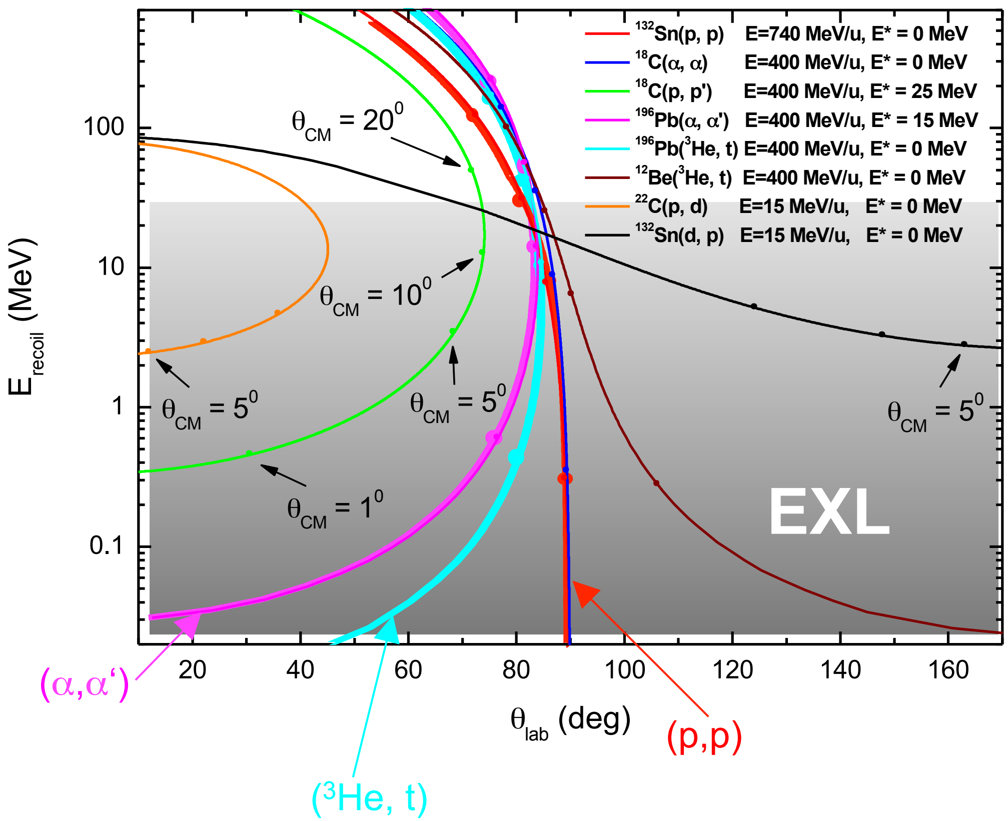
- Investigation of Gamow-Teller Transitions:

  ⇒ weak interaction rates for N = Z waiting point nuclei in the rp-process

  ⇒ electron capture rates in the presupernova evolution (core collaps)

method: (^{3}He,t), (d,^{2}He) charge exchange reactions at low q

Kinematical Conditions for Light-Ion Induced Direct Reactions in Inverse Kinematics



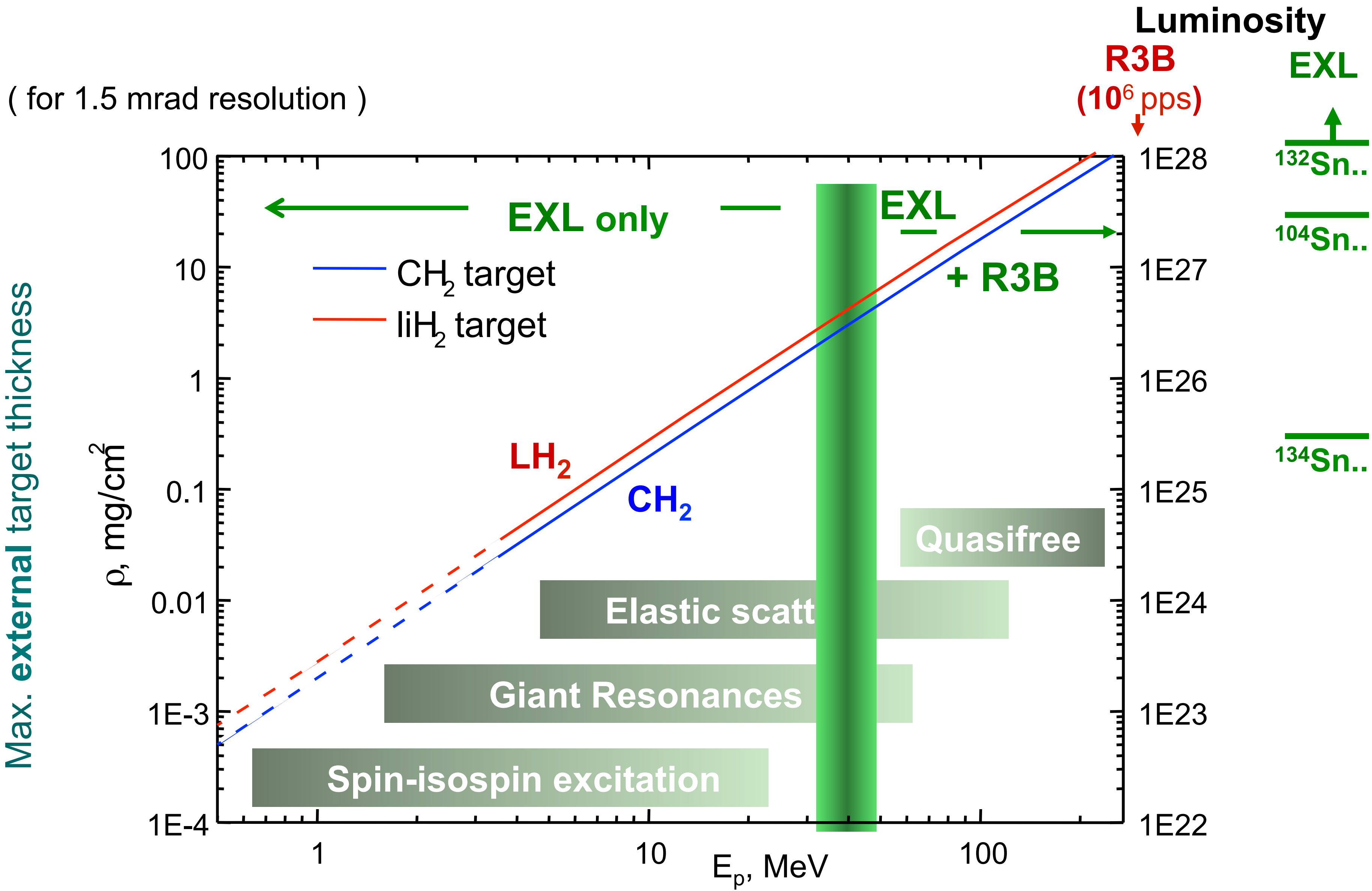
- required beam energies: $E \approx 200 \ldots 740$ MeV/u (except for transfer reactions)
- required targets: ^{1,2}H, ^{3,4}He
- most important information in region of low momentum transfer
  - ⇒ low recoil energies of recoil particles
  - ⇒ need thin targets for sufficient angular and energy resolution

Advantage of Storage Rings for Direct Reactions in Inverse Kinematics

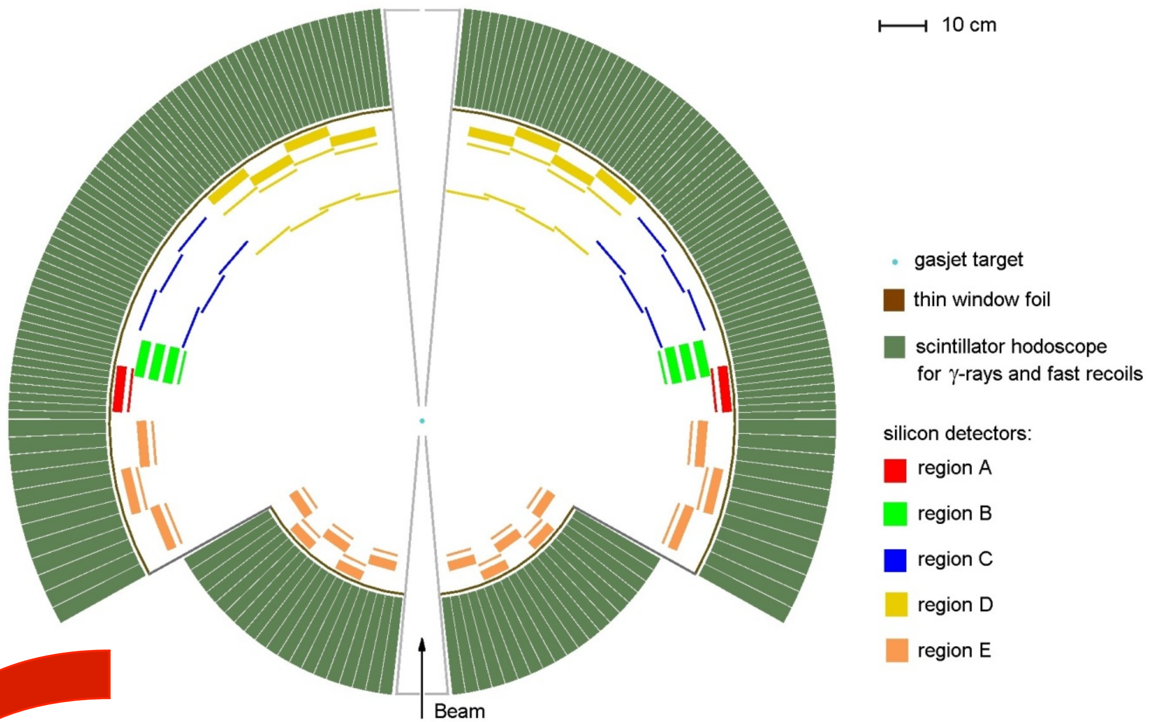
- low threshold and high resolution due to: beam cooling, thin target (10^{14}-10^{15} cm^{-2})
- gain of luminosity due to: continuous beam accumulation and recirculation
- low background due to: pure, windowless $^{1,2}H_2$, $^{3,4}He$, etc. targets
- experiments with isomeric beams

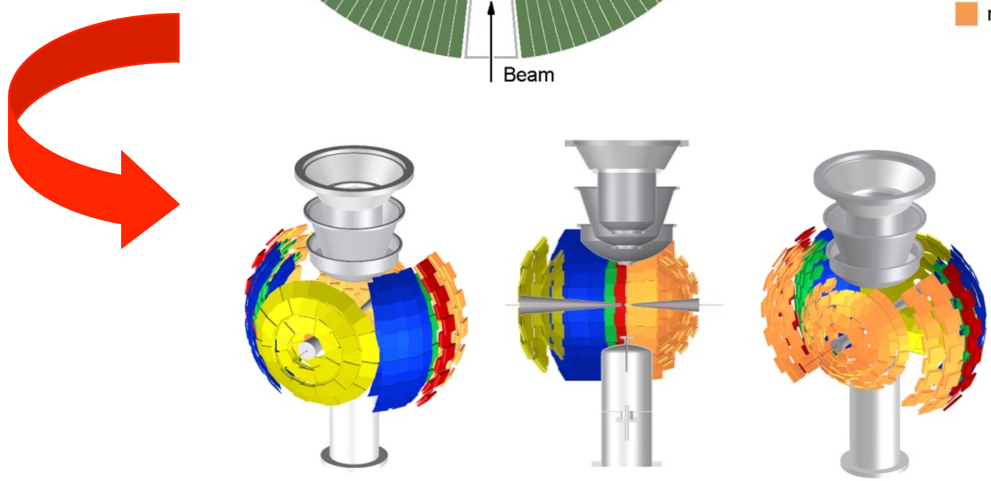
Experiments at very low momentum transfer can only be performed at EXL (except with active targets, but with substantial lower luminosity)

External Target Versus Internal Target



The EXL Recoil and Gamma Array





Si DSSD ⇨ **ΔE, x, y**
300 µm thick, spatial resolution better than 500 µm in x and y,
ΔE = 30 keV (FWHM)

Thin Si DSSD ⇨ **tracking**
<100 µm thick, spatial resolution better than 100 µm in x and y,
ΔE = 30 keV (FWHM)

Si(Li) ⇨ **E**
9 mm thick, large area
100 x 100 mm^2,
ΔE = 50 keV (FWHM)

CsI crystals ⇨ **E, γ**
High efficiency, high resolution, 20 cm thick

II.2. Recent Experiments and Future Perspectives

Proposal E105:
Start up of part of the EXL physics program:

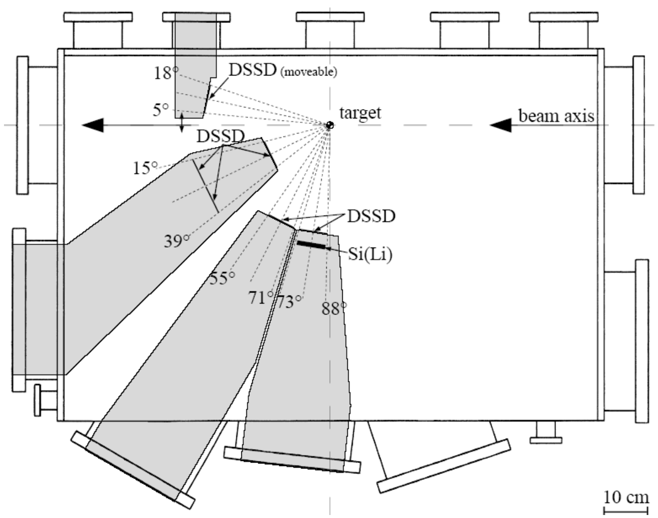
Feasibility Studies and First Experiments with RIB`s at the ESR Storage Ring

Intermediate Solution to Overcome the Limitations of the MSV (First Phase of FAIR):

Task Force established

Proposal E105: Feasibility Studies and First Experiments with RIB`s at the ESR Storage Ring

specially designed scattering chamber for the ESR:



reactions with ^{58}Ni:

proof of principles and feasibility studies:

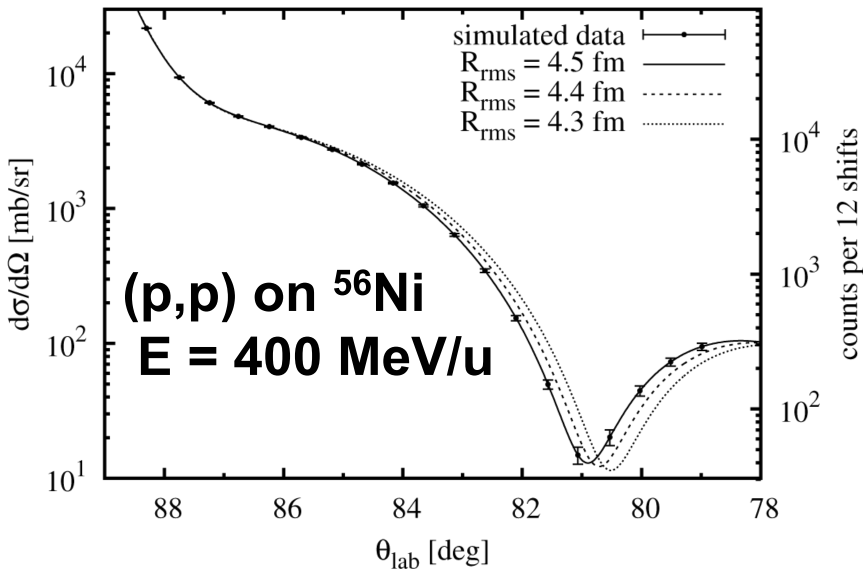
- UHV capability of detector setup
- background conditions in ESR environment at the internal target
- low energy threshold
- beam and target performance

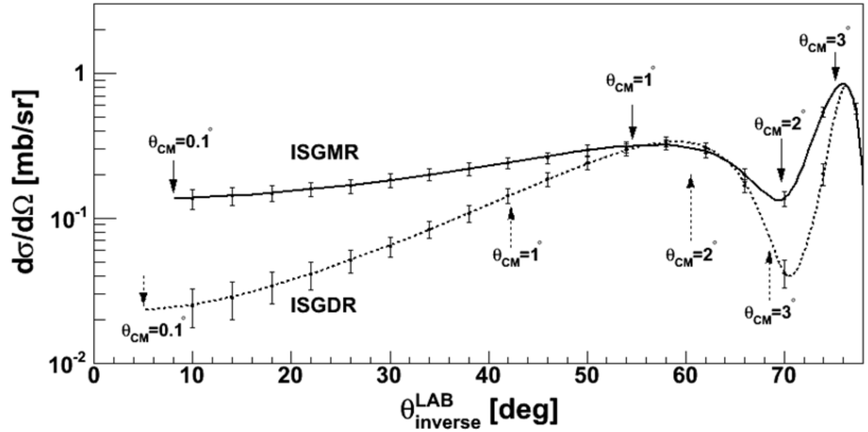
reactions with ^{56}Ni:

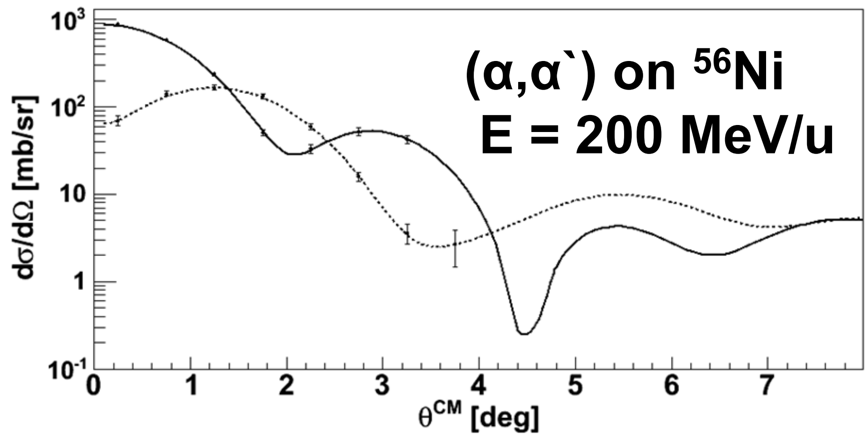
^{56}Ni: doubly magic nucleus!!

- (p,p) reactions: nuclear matter distribution
- (α,α`) reactions: giant resonances (GMR) EOS parameters (nucl. compressibility)
- (^{3}He,t) reactions: Gamow-Teller matrix elements, important for astrophys.

Theorectical Predictions





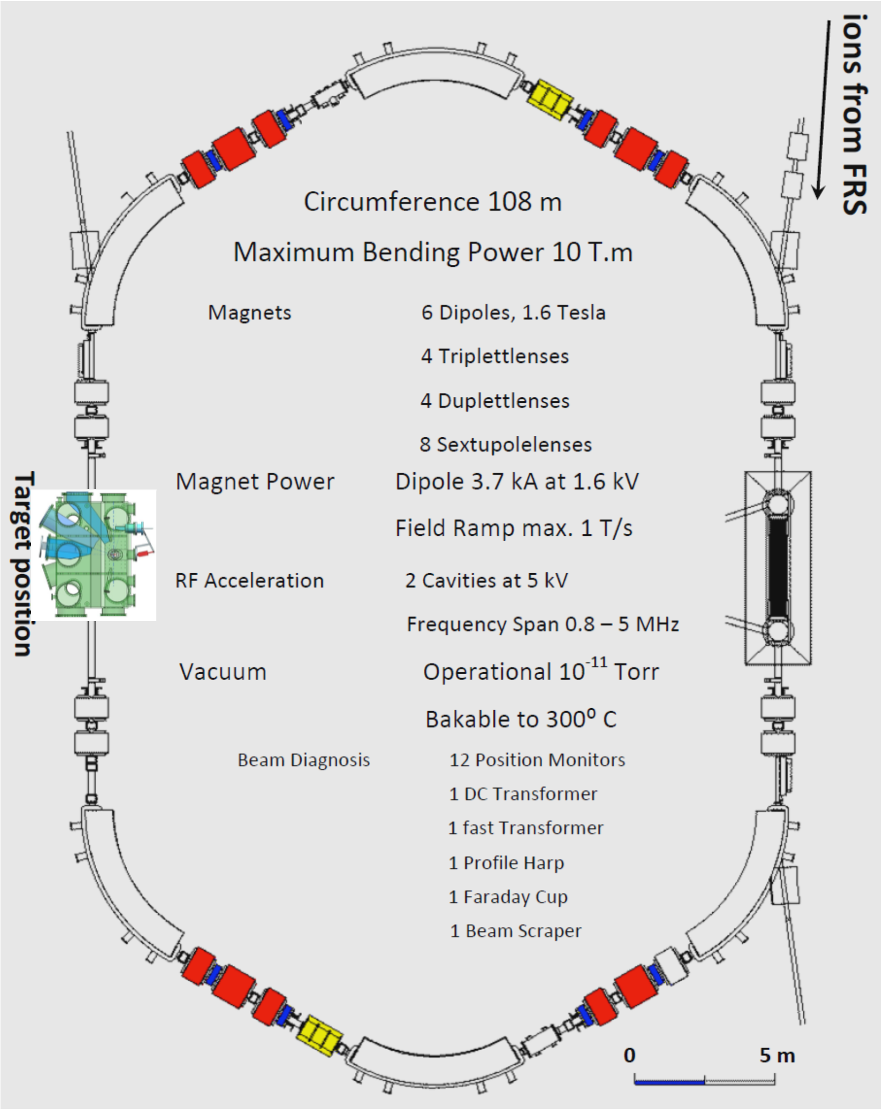


4 days with L = 10^{25} cm^{-2} sec^{-1}
recoil energies: 1 – 45 MeV

14 days with L = 10^{25} cm^{-2} sec^{-1}
recoil energies: 200 – 700 keV

needed: large solid angle detectors with low threshold and large dynamic range

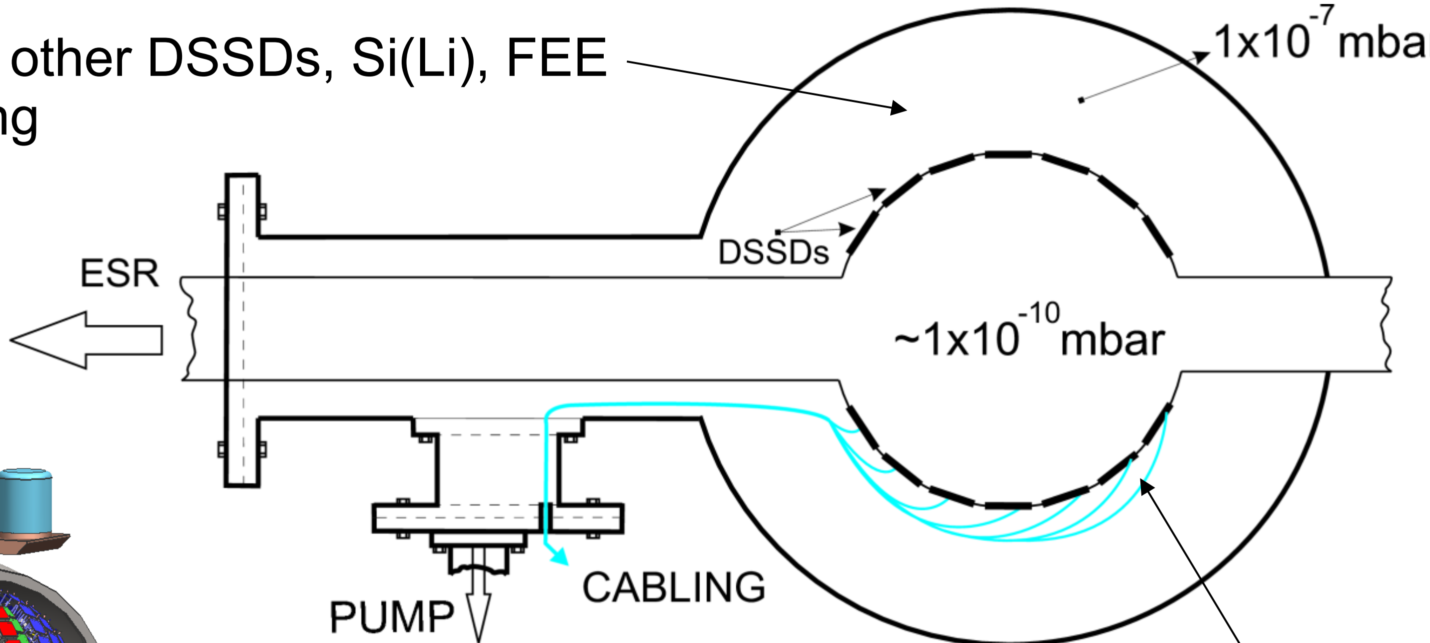
Setup at the ESR Storage Ring

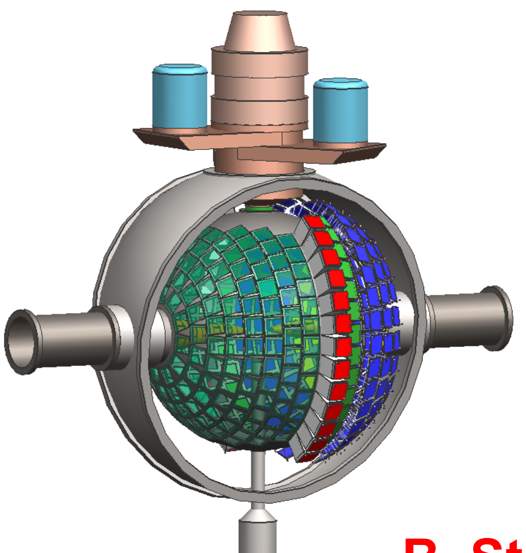


UHV Capability of the EXL Silicon Array:
Concept: using DSSD`s as high vacuum barrier

- Differential pumping proposed to separate (N)ESR vacuum from EXL instrumentation (cabling, FEE, other detectors)

Space for other DSSDs, Si(Li), FEE and cabling

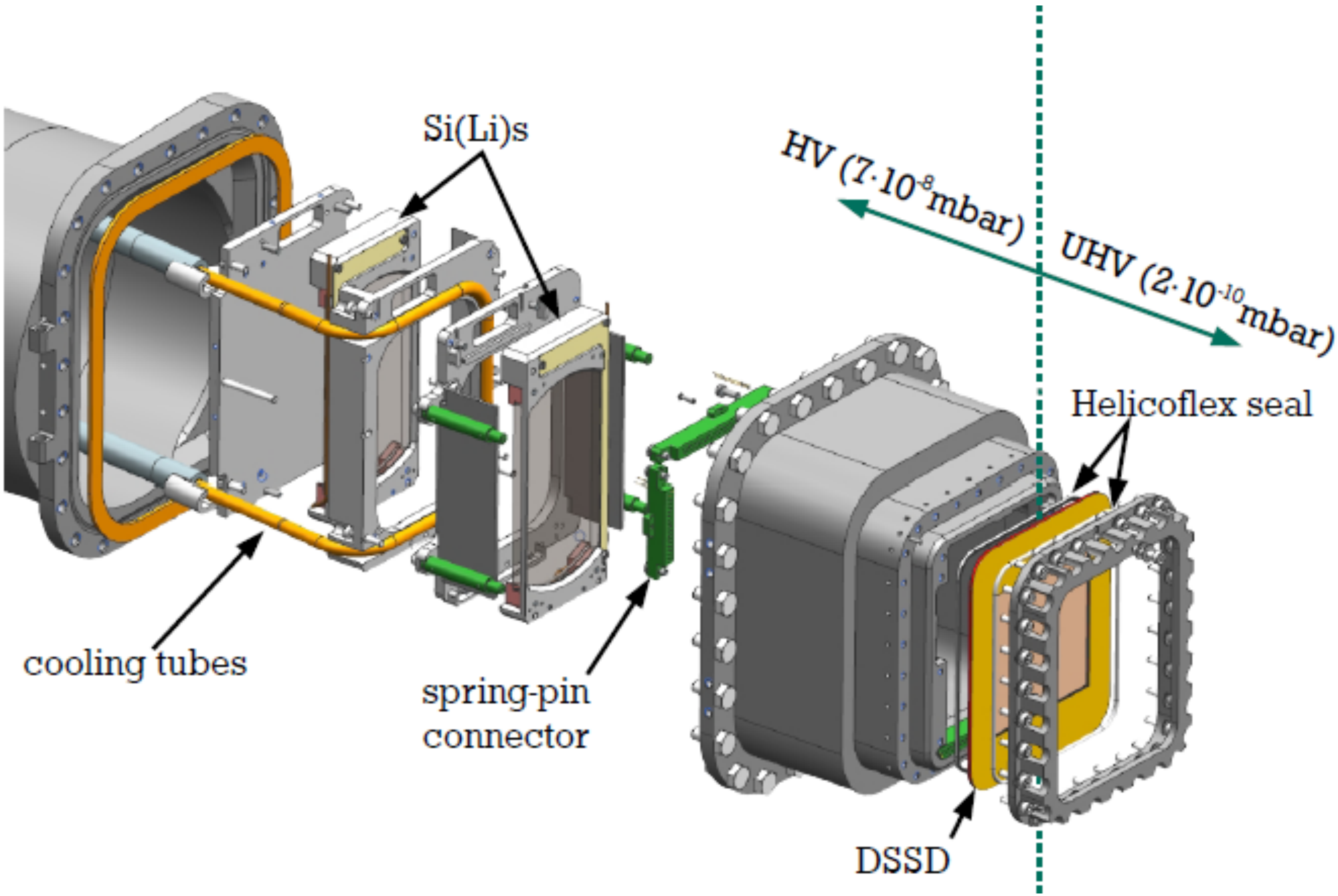




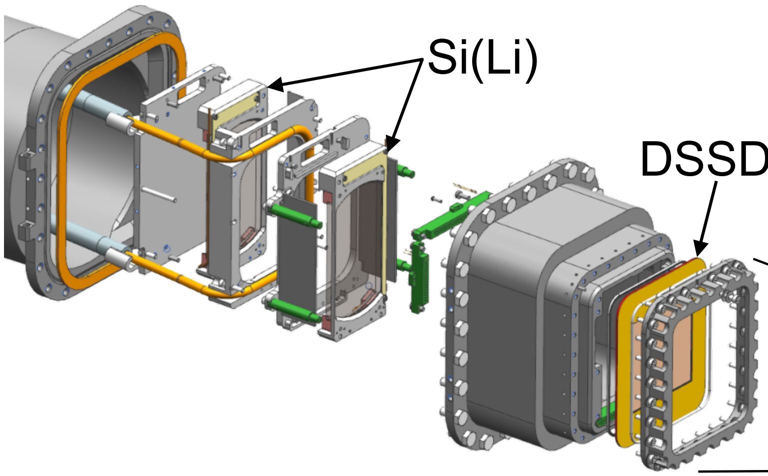
Inner shell of DSSDs on support frame forms (bakeable) vacuum barrier

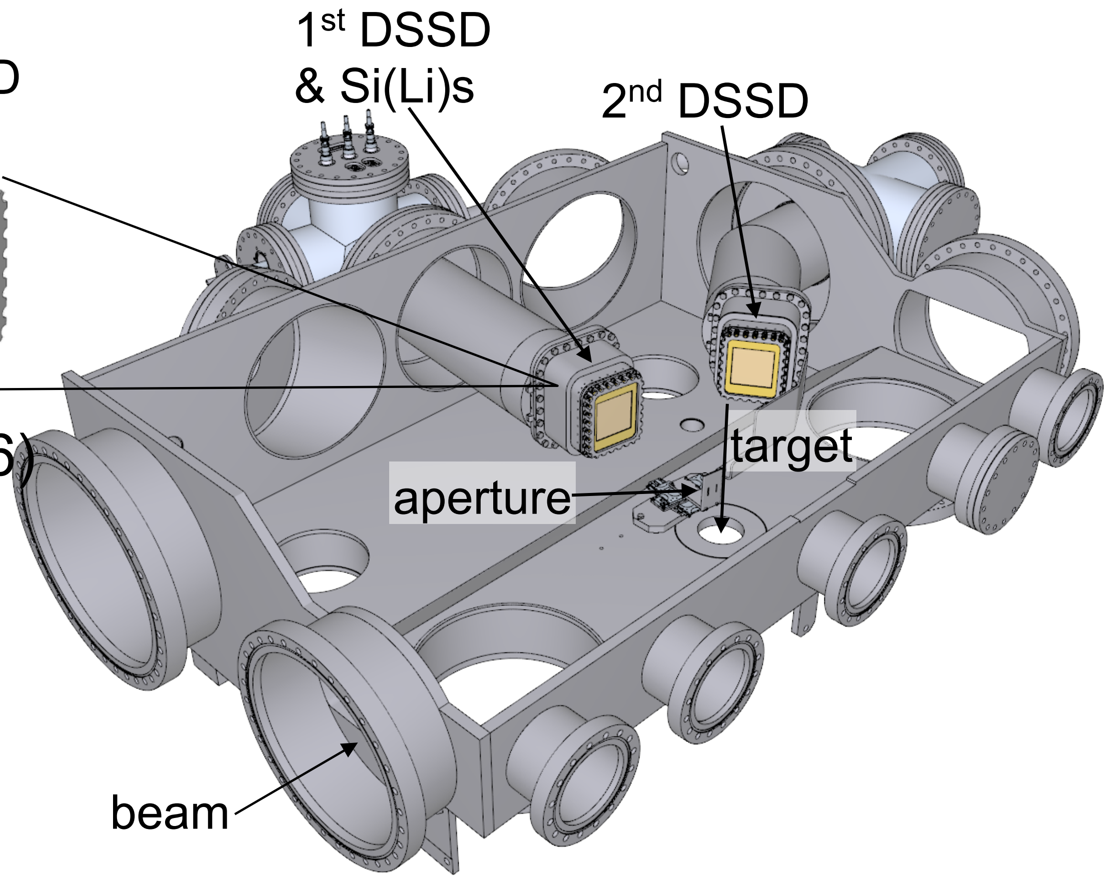
B. Streicher et al., Nucl. Instr. Meth. A654 (2011) 604

Experimental Concept



Experimental Concept for the E105 Experiment

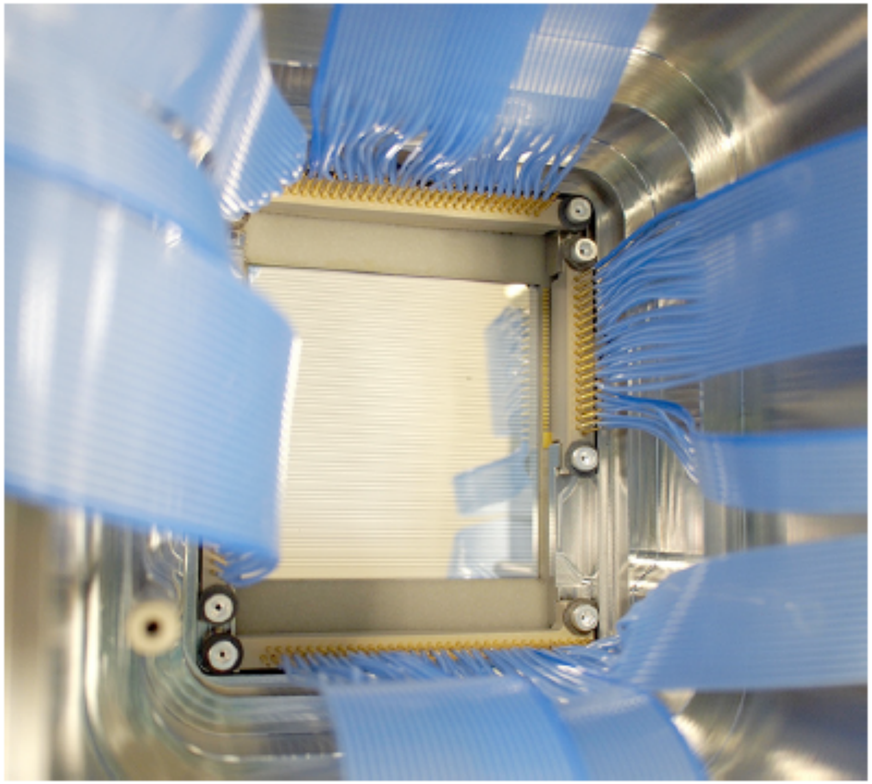




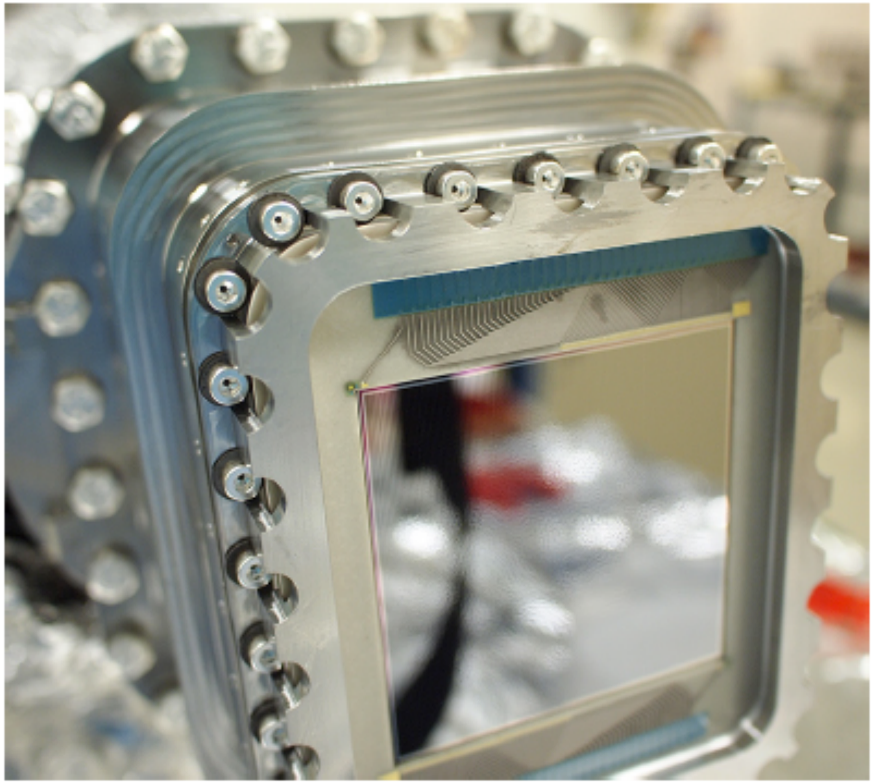
- **DSSD**: 128×64 strips, (6×6) cm², 285 μm thick
- **Si(Li)**: 8 pads, (8×4) cm², 6.5 mm thick
- **active vacuum barrier**
- **moveable aperture** to improve angular resolution

Experimental Concept for the E105 Experiment

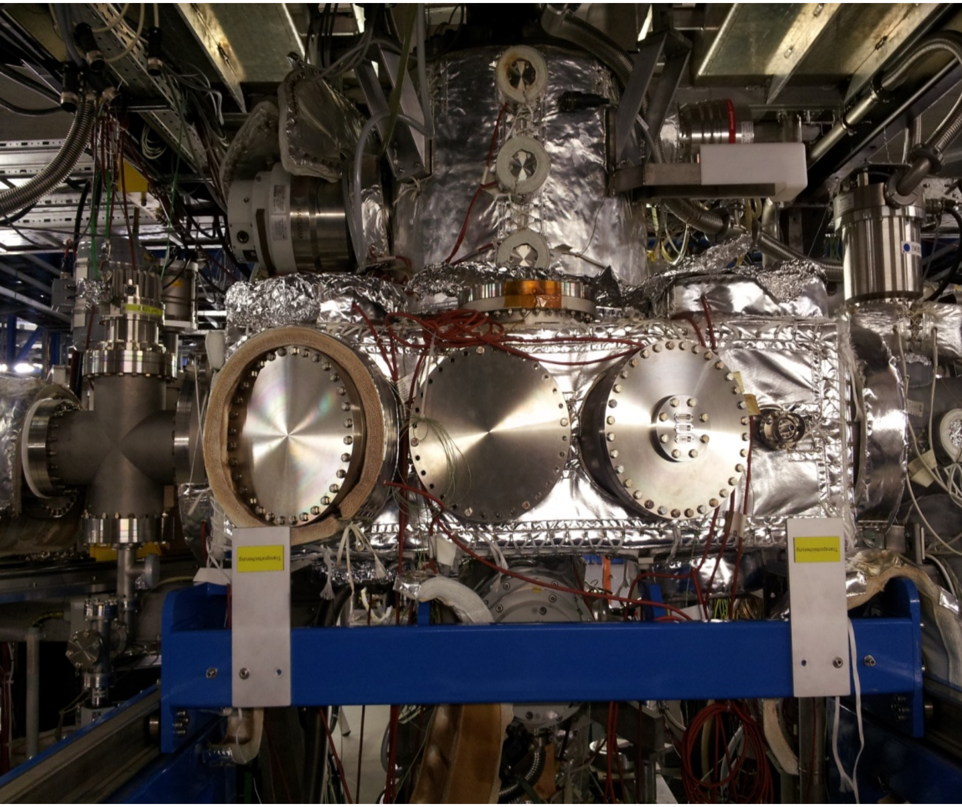
- Auxilliary vacuum side



- Ultra-high vacuum side

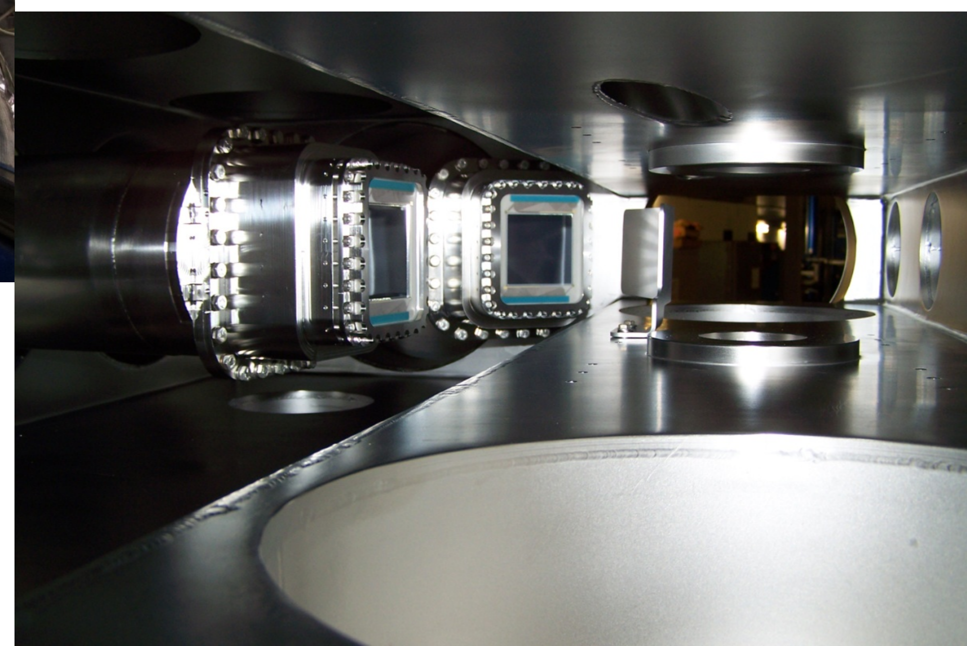


Experimental Setup at the ESR

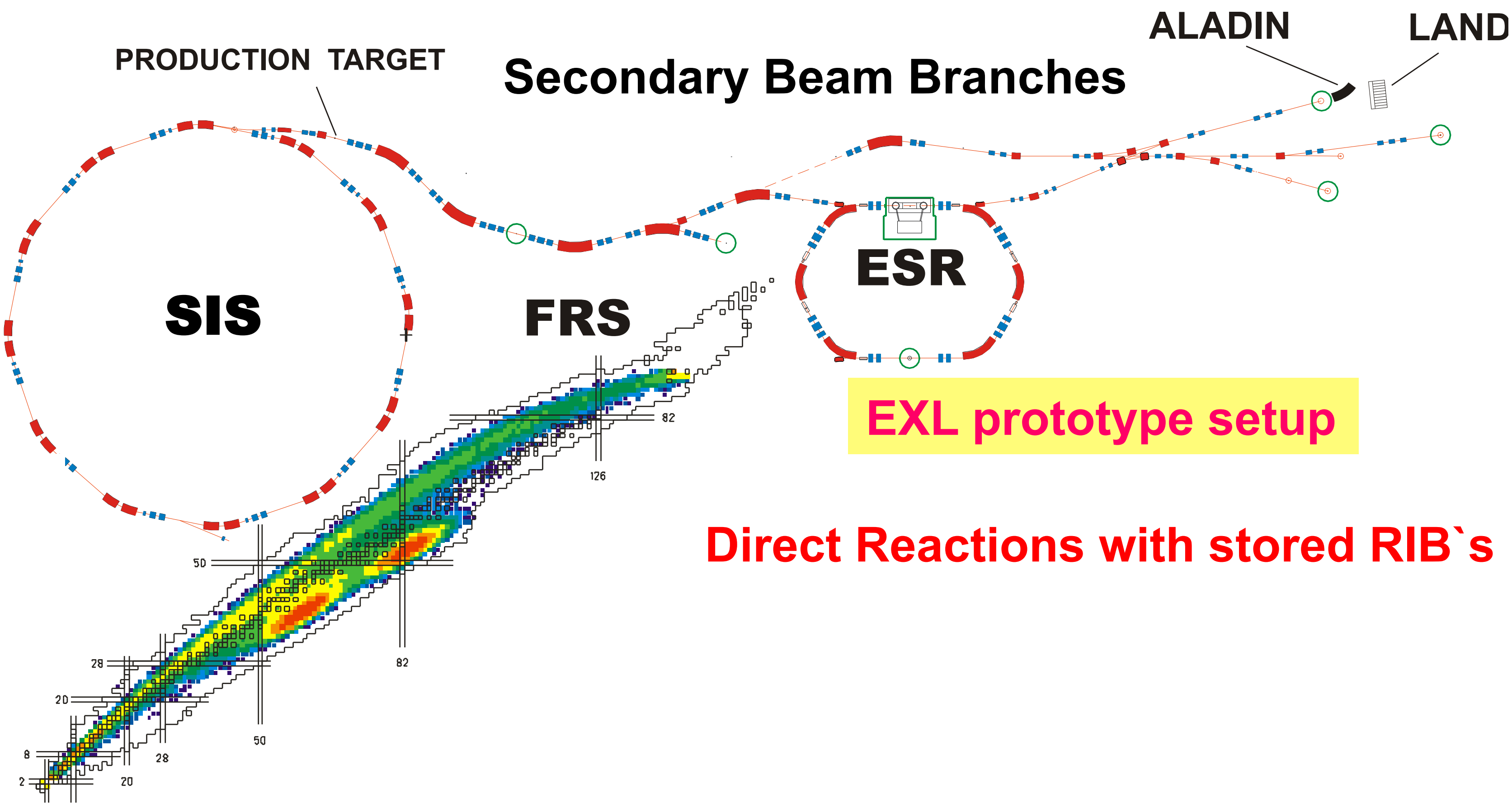


Scattering Chamber mounted at the Internal Target of the ESR

challenge:
UHV capable and bakeable DSSD and Si(Li) detectors



FRS: In-Flight Separator & High-Resolution Spectrometer



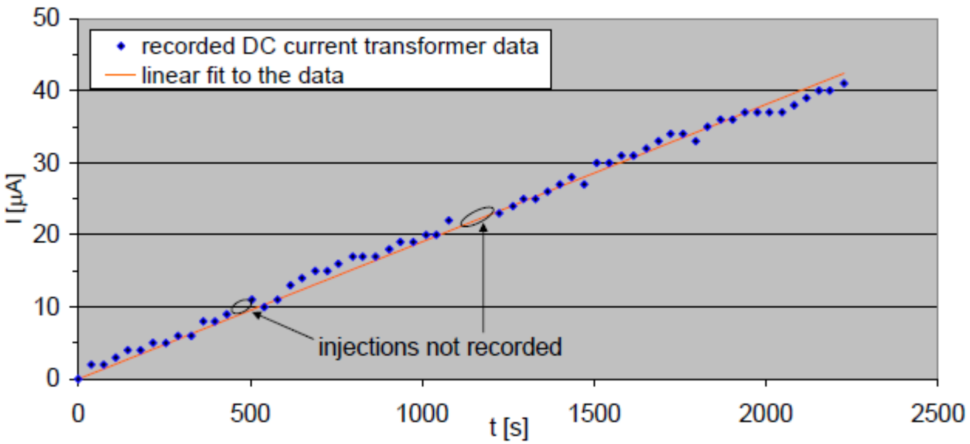
Preparation of the Stored Radioactive ^{56}Ni Beam

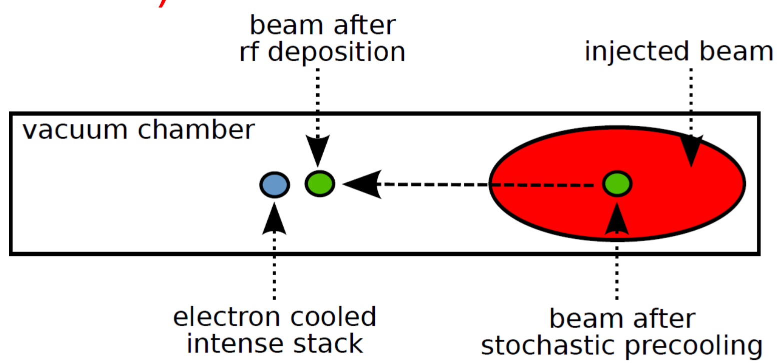
FRS: fragmentation of 600 MeV/u ^{58}Ni beam

injection to ESR: **7 x 10^{4}** ^{56}Ni per injection

stochastic cooling, bunching and stacking (60 injections):

4.8 x 10^{6} ^{56}Ni in the ring



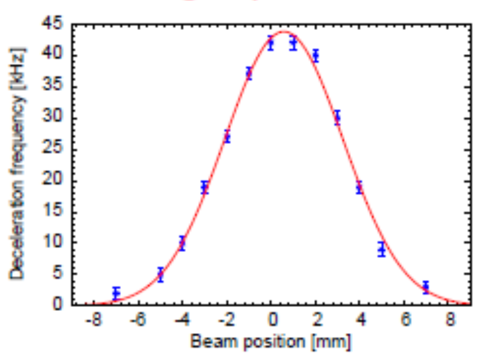


luminosity: H_2 target: 2×10^{13} cm^{-2}

$\Rightarrow$ **L = 2 x 10^{26} cm^{-2} sec^{-1}**

(reduced by aperture)

target profile

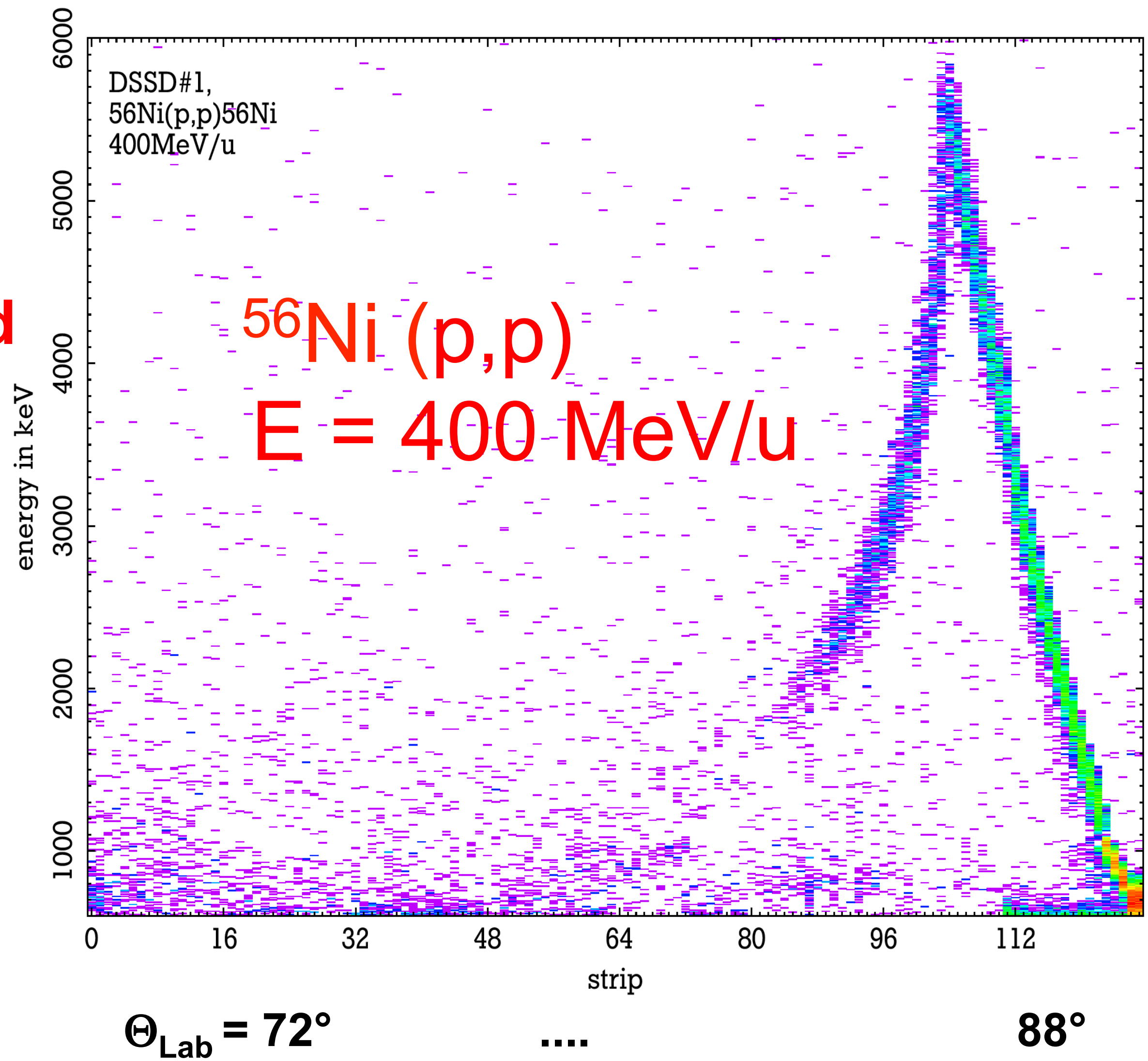


σ = 3.78 mm x_0 = 0.58 mm

First Results with Radioactive Beam

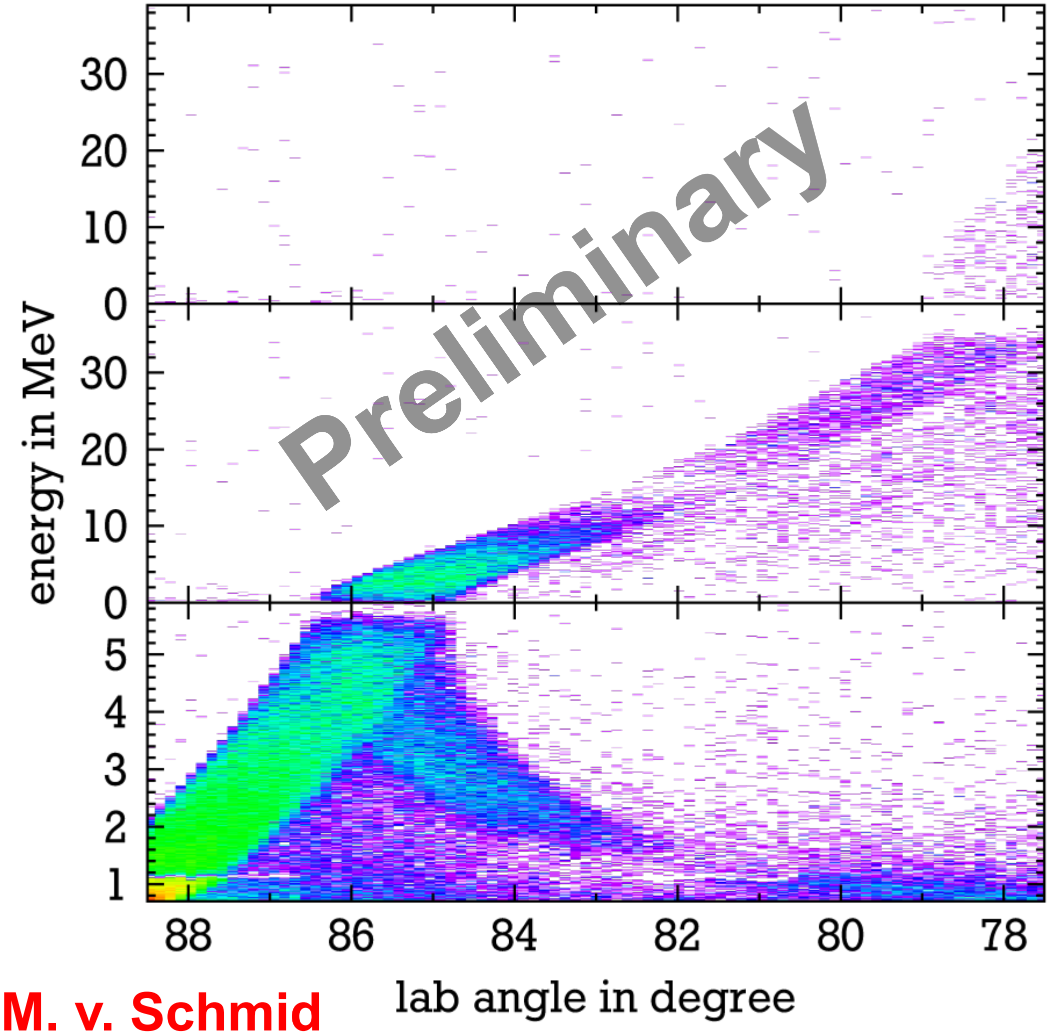
25. 10. 2012:

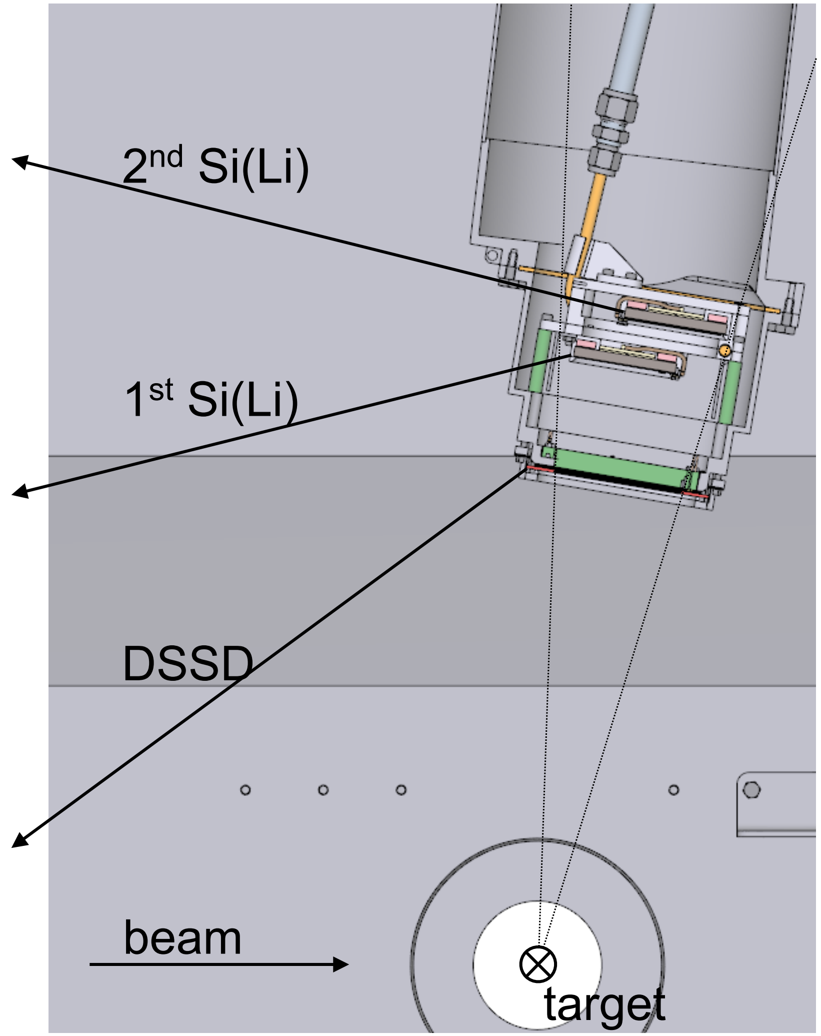
First Nuclear Reaction Experiment with Stored Radioactive Beam!!!!



First Results with Radioactive Beam

^{56}Ni(p,p), E = 400 MeV/u **Response of Individual Detectors**

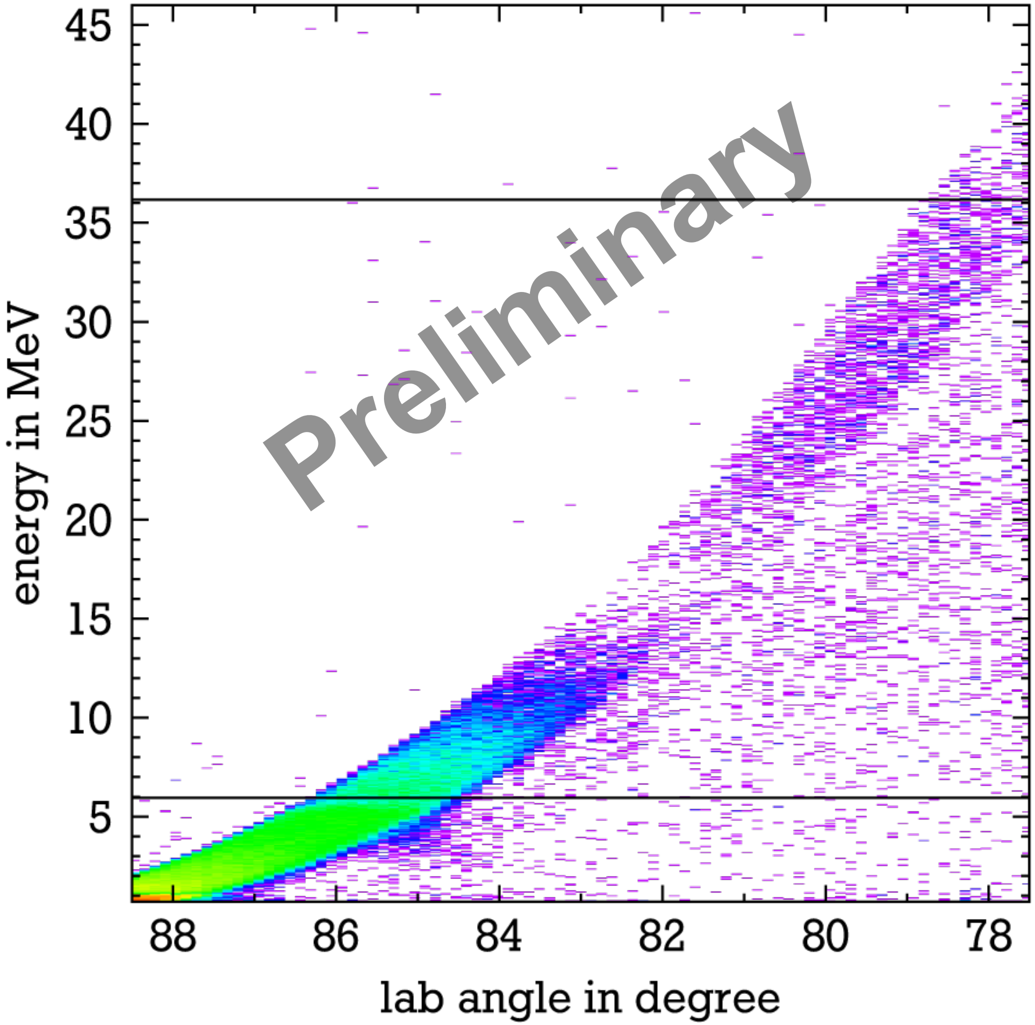


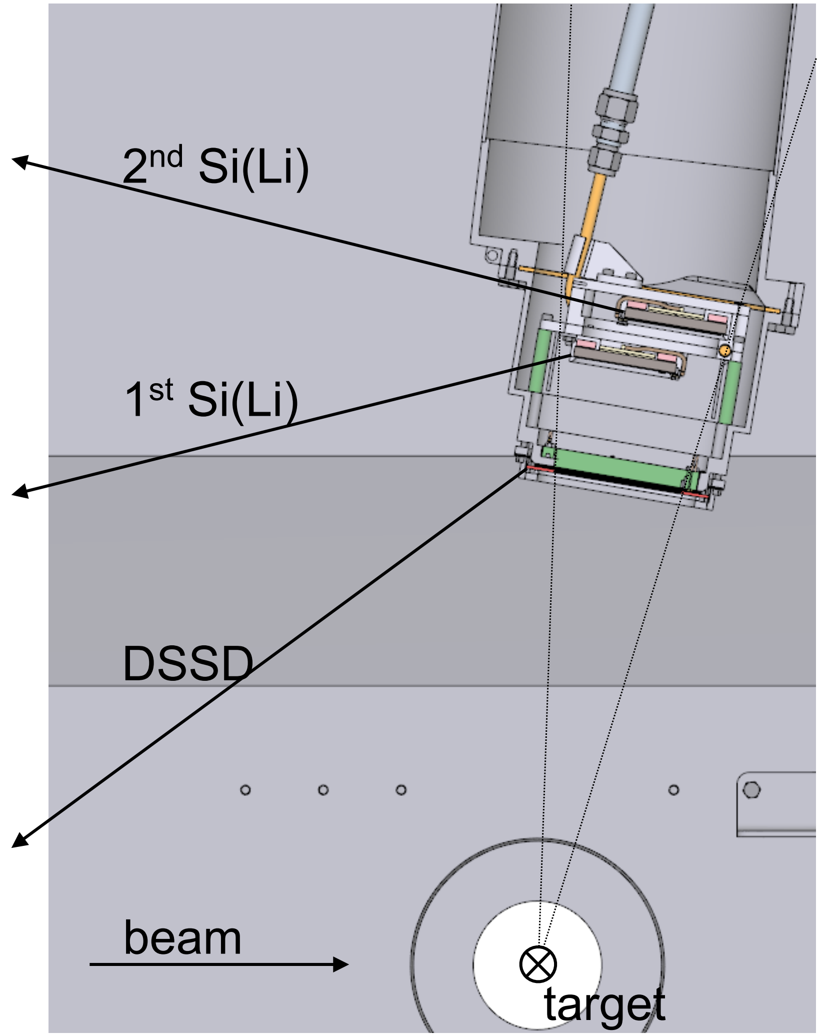


M. v. Schmid

First Results with Radioactive Beam

$^{56}Ni(p,p)$, E = 400 MeV/u Reconstructed Energy

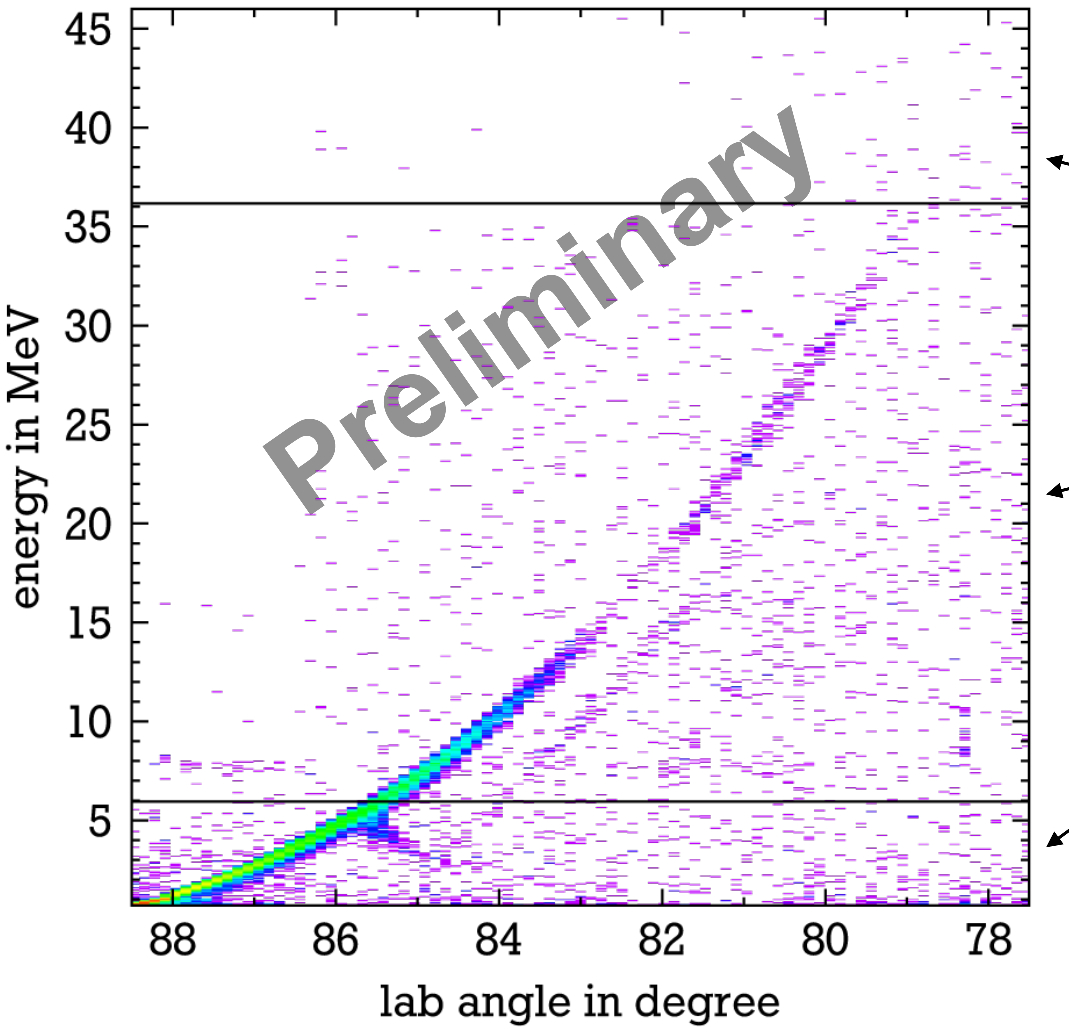


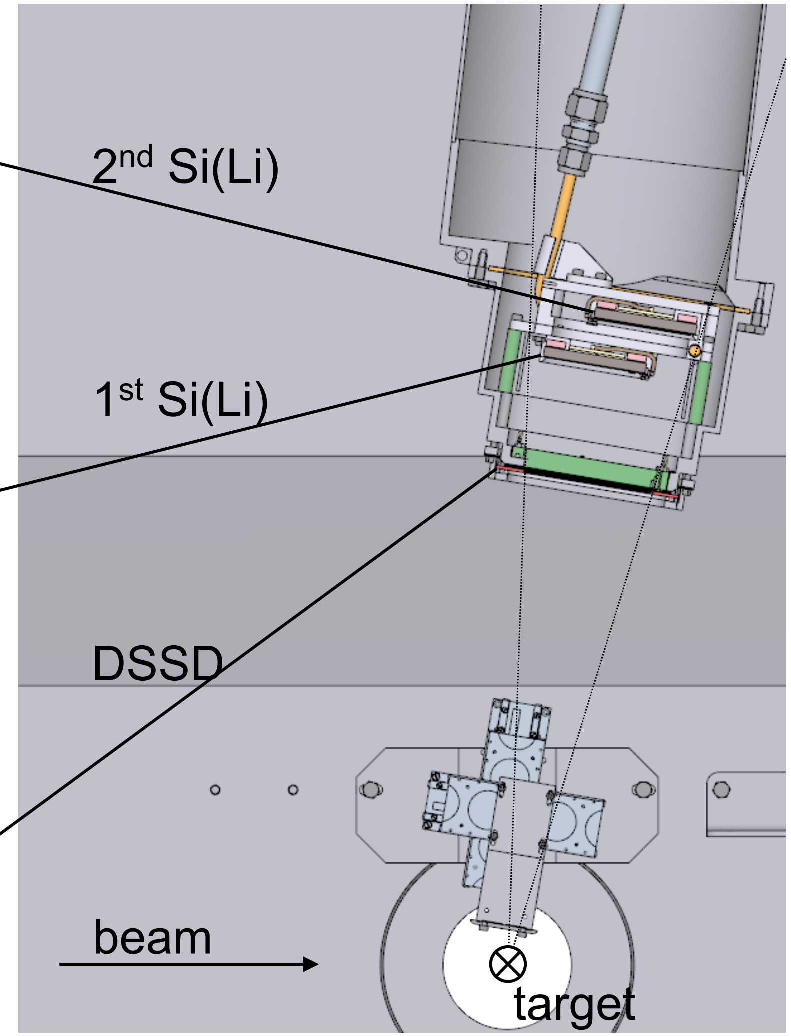


First Results with Radioactive Beam

^{56}Ni(p,p), E = 400 MeV/u

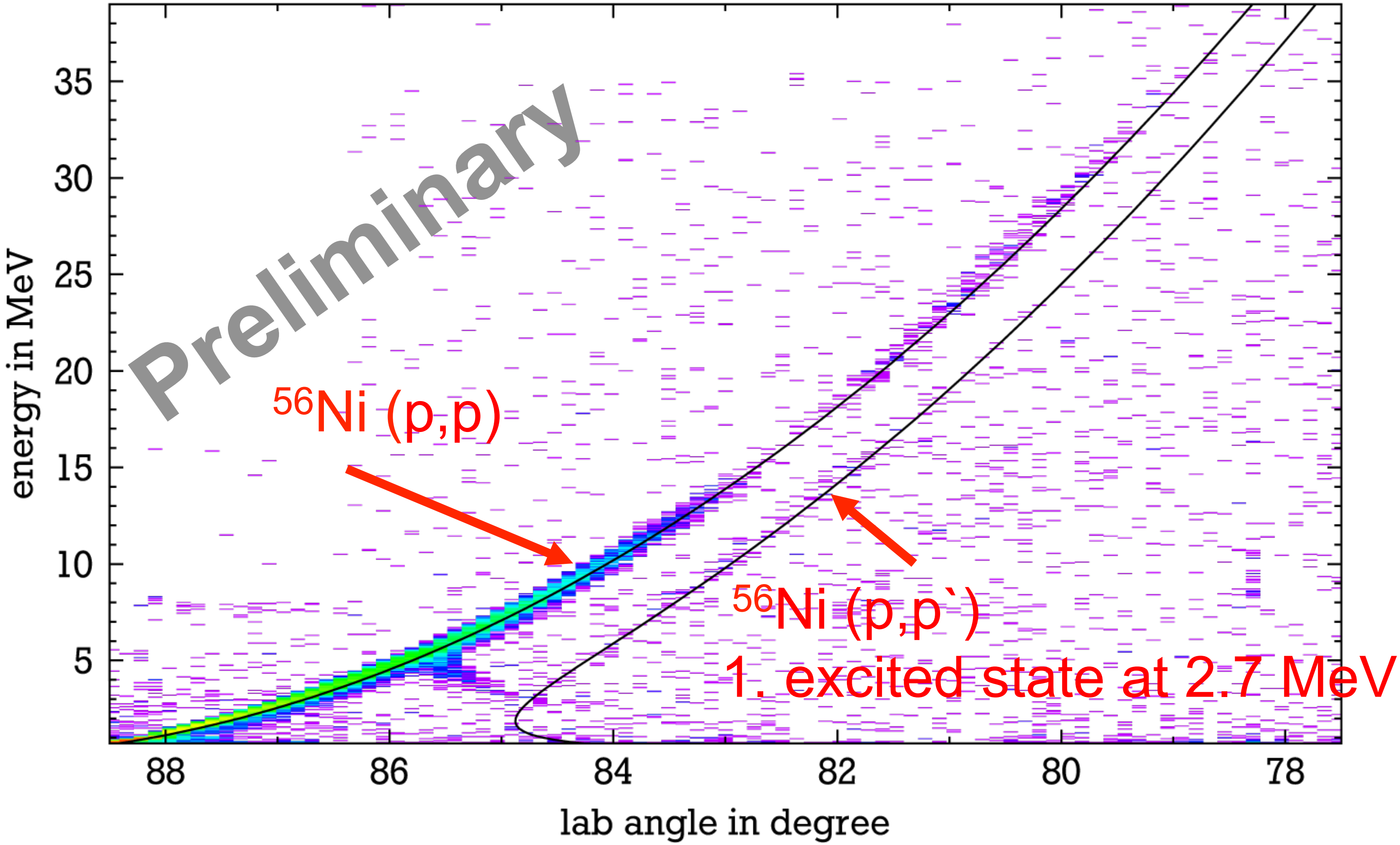
Benefit of the 1mm Aperture





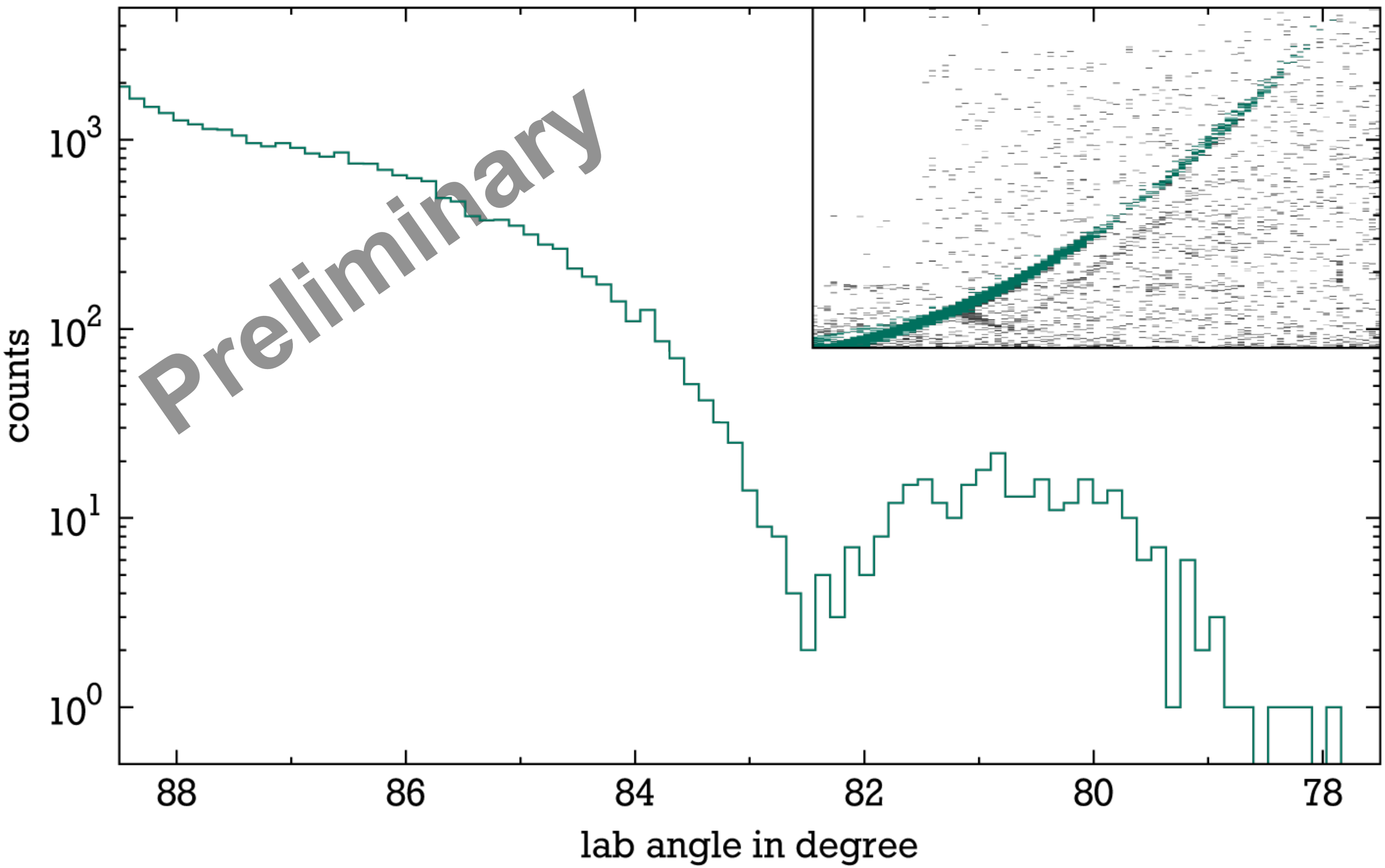
First Results with Radioactive Beam

^{56}Ni(p,p`), E = 400 MeV/u   Identification of Inelastic Scattering



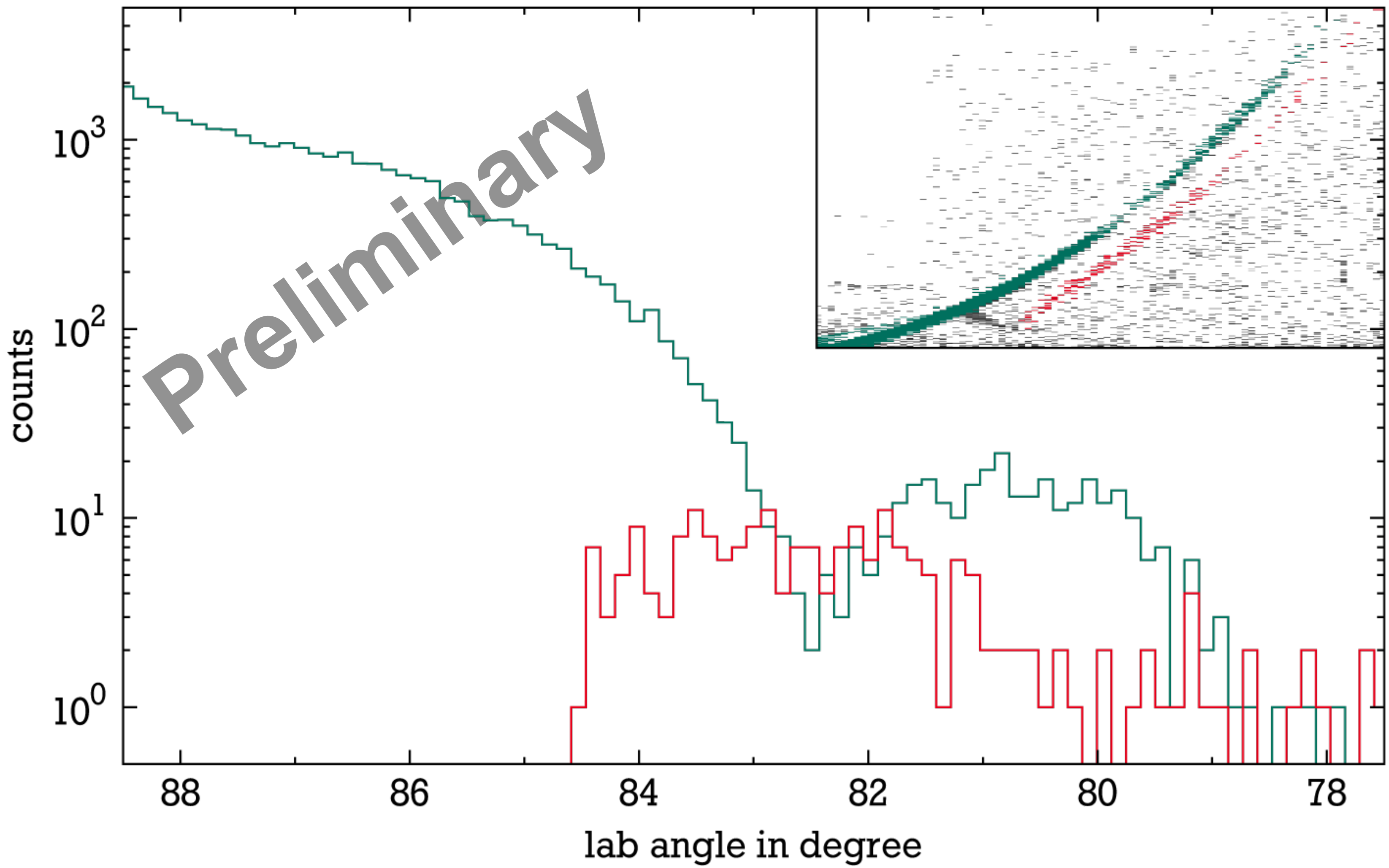
First Results with Radioactive Beam

$^{56}Ni(p,p)$, E = 400 MeV/u Angular Distribution



First Results with Radioactive Beam

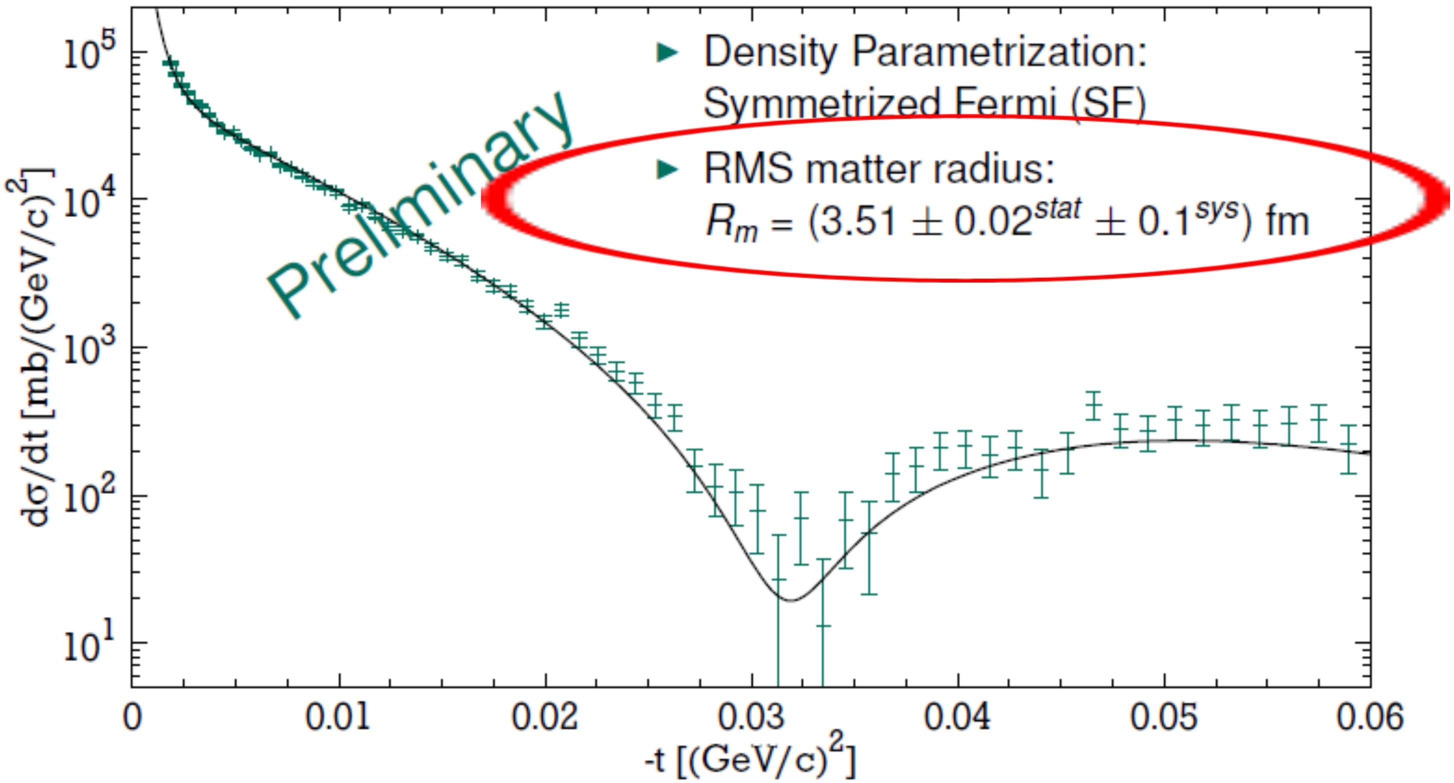
$^{56}Ni(p,p)$, E = 400 MeV/u Angular Distribution



First Results with Radioactive Beam

^{56}Ni(p,p), E = 400 MeV/u Angular Distribution

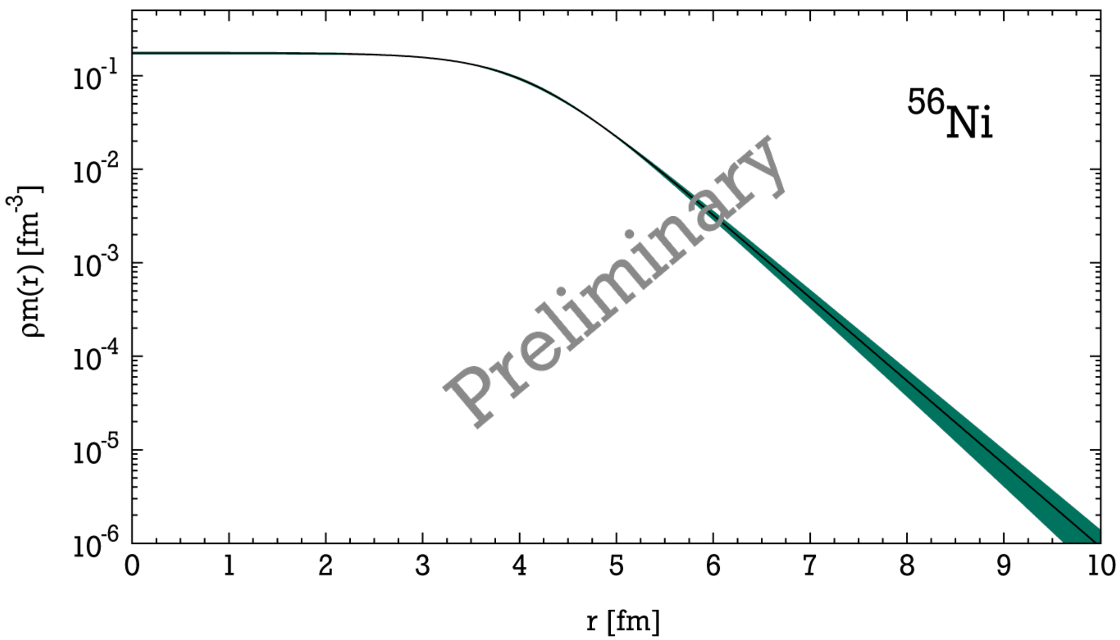
Cross Section fitted using the Glauber Theory



M. v. Schmid et al., to be published

First Results with Radioactive Beam

Nuclear Matter Distribution of ^{56}Ni

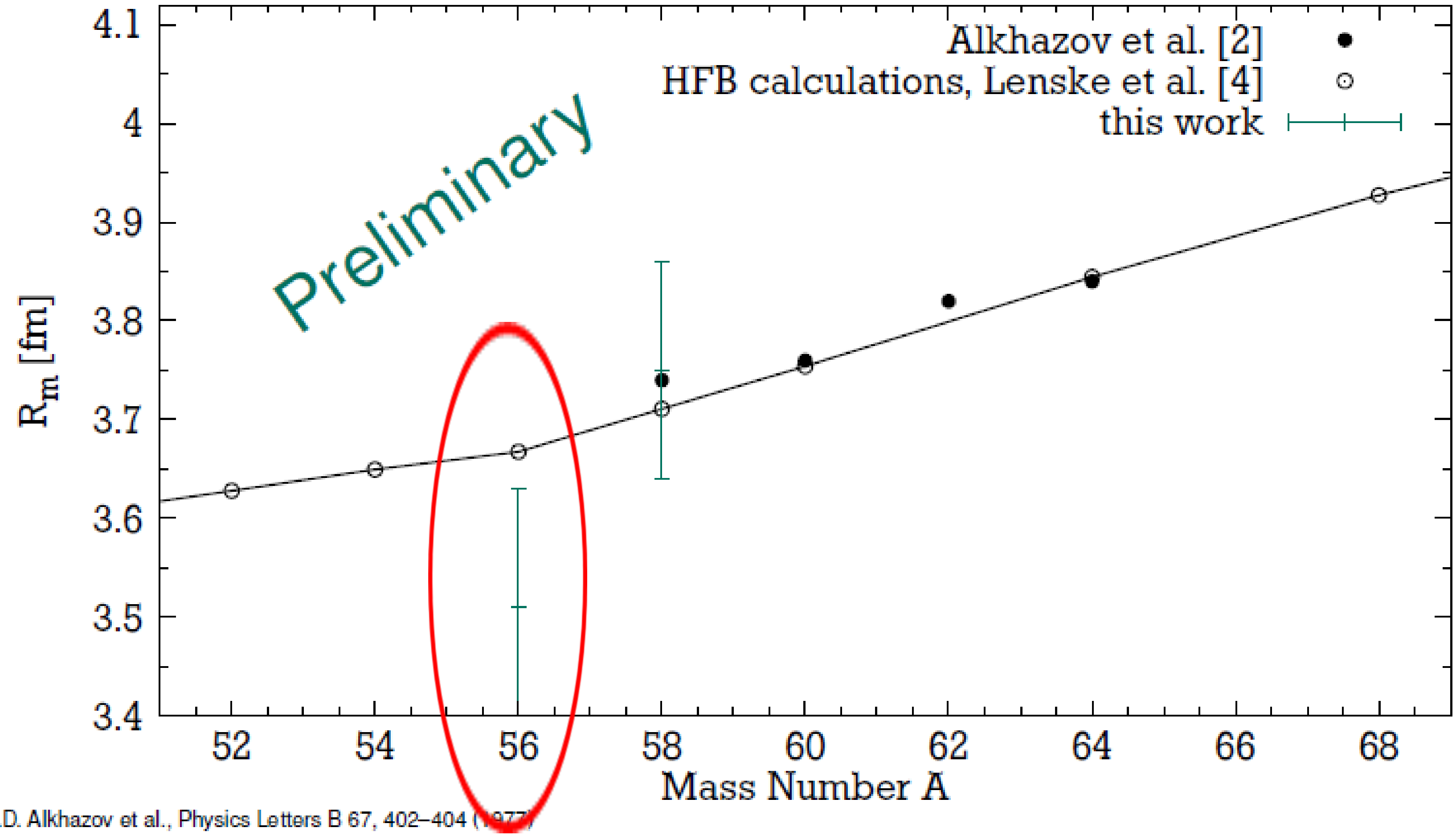


comparison with theoretical predictions:

reference	Rmatter[fm]
present work	3.51 (10)
H. Lenske et al. Phys. Lett. B 647 (2007) 82	3.66
K. Oyamatsu et al. Progr.Theor. Phys. 109 (2003) 631	3.54

M. v. Schmid et al., to be published

Nuclear Matter Radii in Ni Isotopes

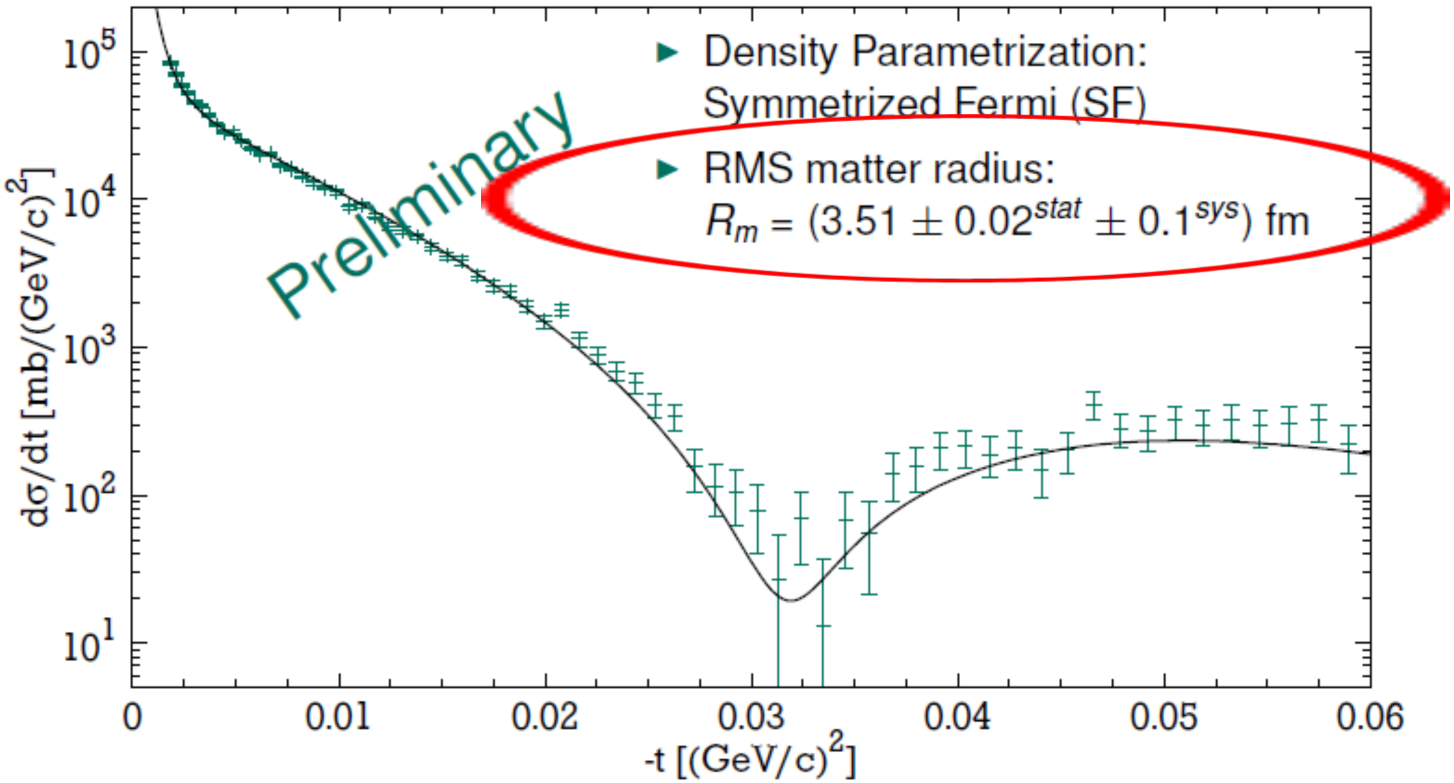


[4] G.D. Alkhazov et al., Physics Letters B 67, 402–404 (1977)
[5] H. Lenske, Physics Letters B 647, 82–87 (2007)

First Results with Radioactive Beam

^{56}Ni(p,p), E = 400 MeV/u Angular Distribution

Cross Section fitted using the Glauber Theory



to be performed: analysis with Sum-of Gaussians density parametrization

⇒ more model independent results

Comparison with External Target Experiment

VOLUME 73, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1994

Proton Inelastic Scattering on ^{56}Ni in Inverse Kinematics

G. Kraus, P. Egelhof, C. Fischer, H. Geissel, A. Himmler, F. Nickel, G. Münzenberg, W. Schwab, and A. Weiss
Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany

J. Friese, A. Gillitzer, H. J. Körner, and M. Peter
Technische Universität München, D-85748 Garching, Germany

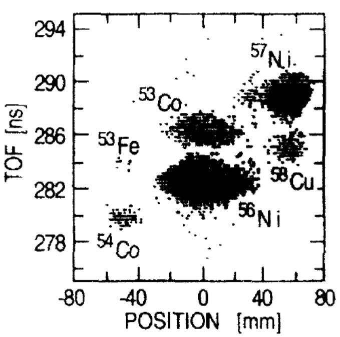
W. F. Henning and J. P. Schiffer
Argonne National Laboratory, Argonne, Illinois 60439

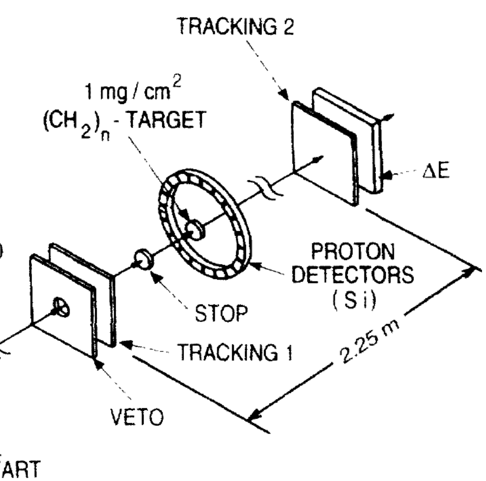
J. V. Kratz
University of Mainz, D-55099 Mainz, Germany

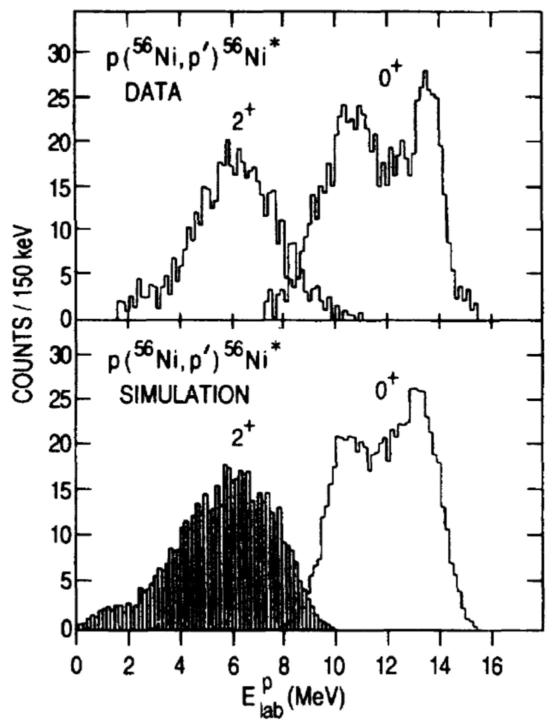
L. Chulkov, M. Golovkov, and A. Ogloblin
I. V. Kurchatov Institute, Moscow, Russia

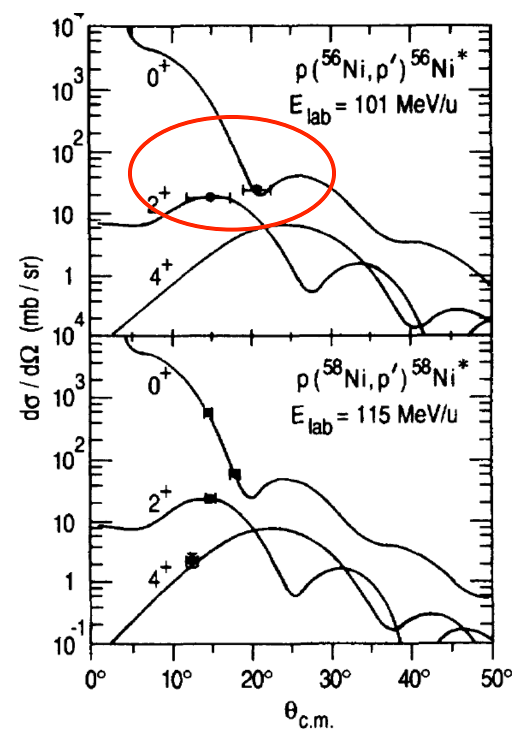
B. A. Brown
Michigan State University, East Lansing, Michigan 4882
(Received 19 May 1994)

same ^{56}Ni intensity
as for ESR experiment









Investigation of the Giant Monopole Resonance in ^{58}Ni

reaction: ^{58}Ni on He target

energy: 100 MeV/u

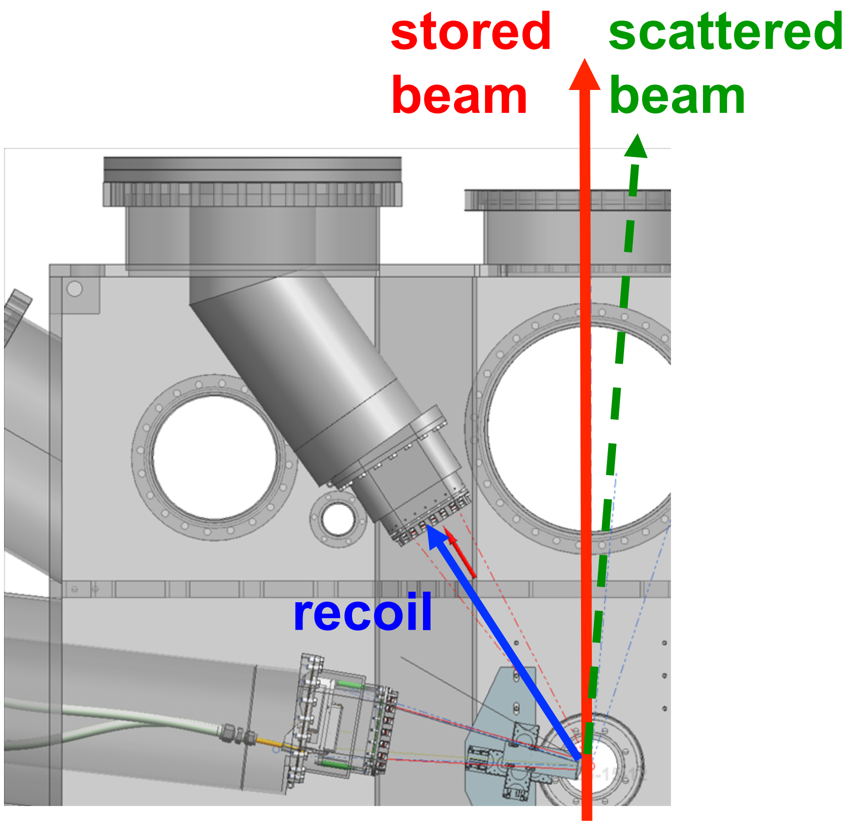
target: 8 X 10^{12} /cm^3

detectors: DSSD

Θ_{Lab} = 27° - 38°

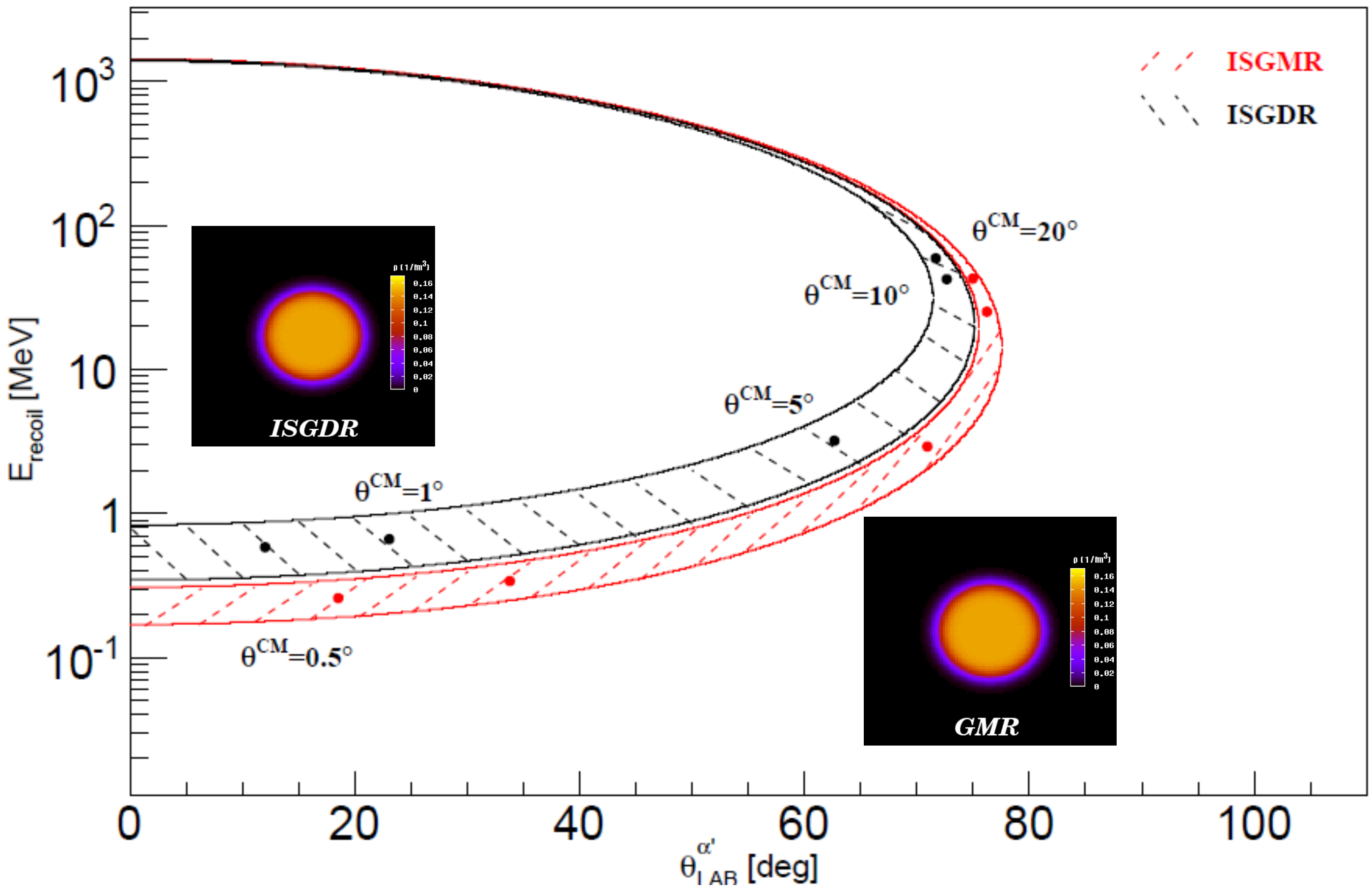
PIN diodes

Θ_{Lab} = 0.2° - 1°



Investigation of the Giant Monopole Resonance in ^{58}Ni

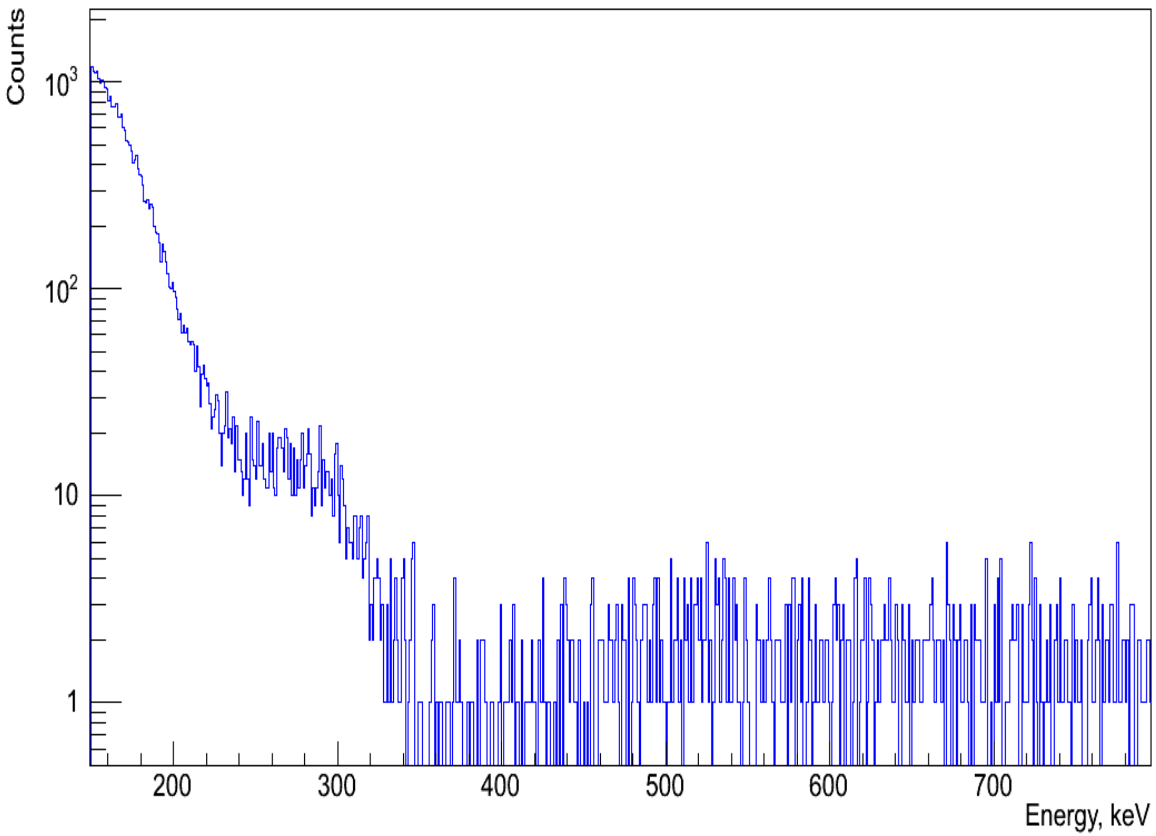
^{58}Ni(α,α`), E = 100 MeV/u



challenge: detect and identify very low energy recoils

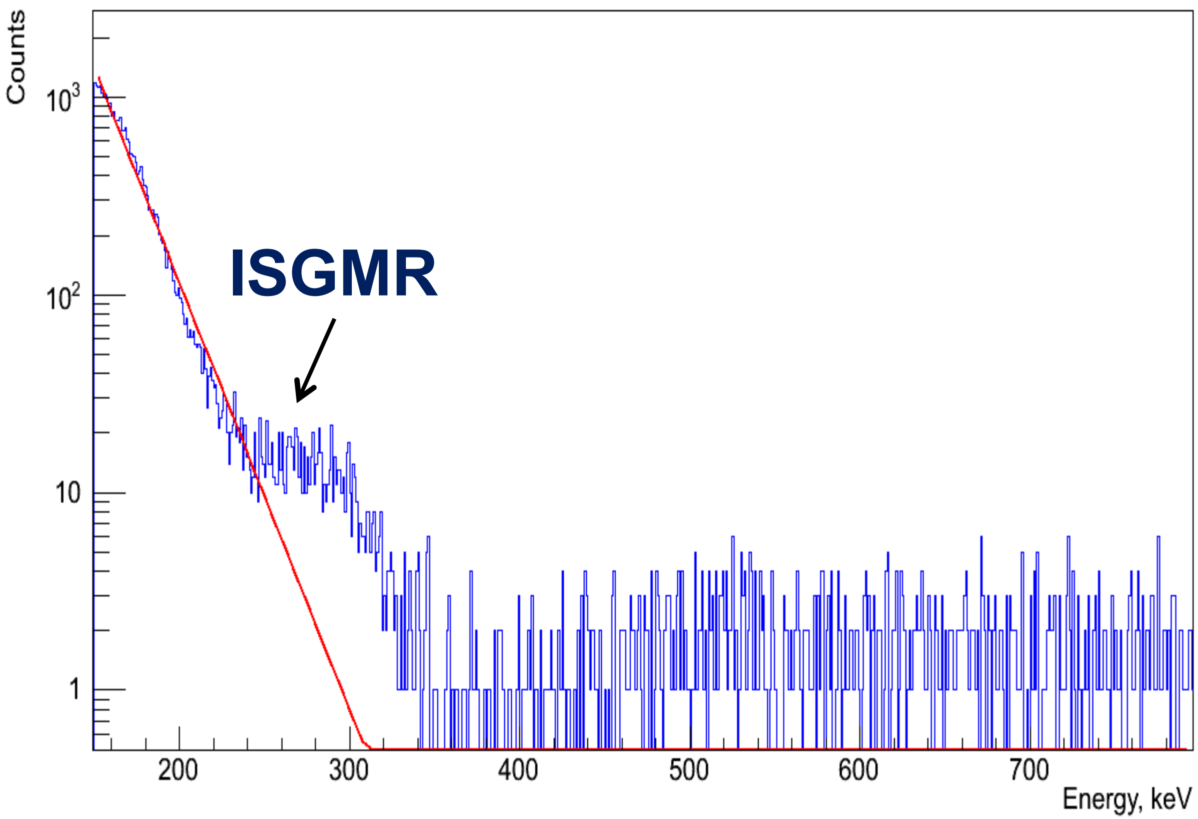
Investigation of the Giant Monopole Resonance in ^{58}Ni

$^{58}Ni(\alpha,\alpha`)$, E = 100 MeV/u, Θ_{lab} = 37 deg



Investigation of the Giant Monopole Resonance in ^{58}Ni

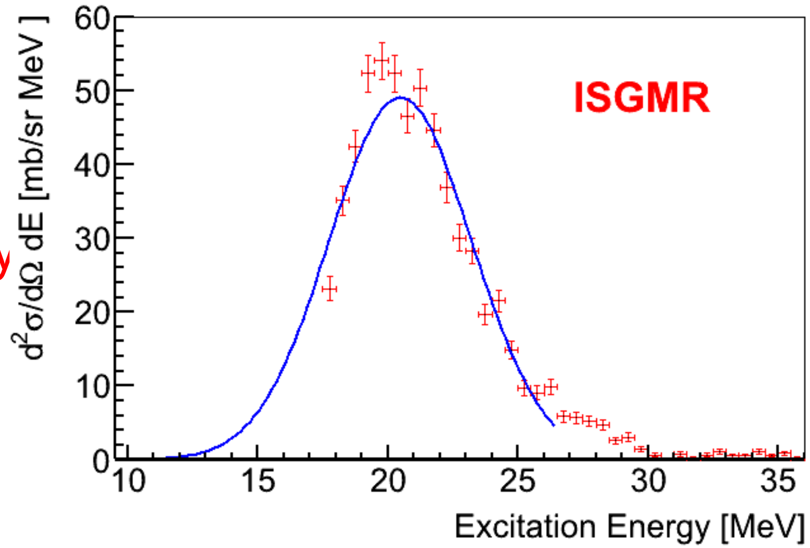
$^{58}Ni(\alpha,\alpha`)$, E = 100 MeV/u, Θ_{lab} = 37 deg

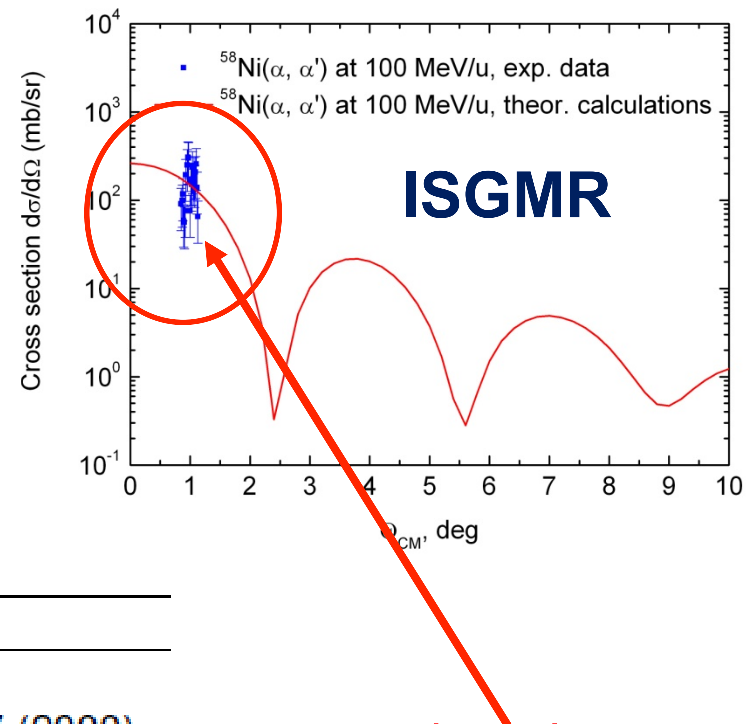


Investigation of the Giant Monopole Resonance in ^{58}Ni

comparison with theoretical prediction:

data preliminary





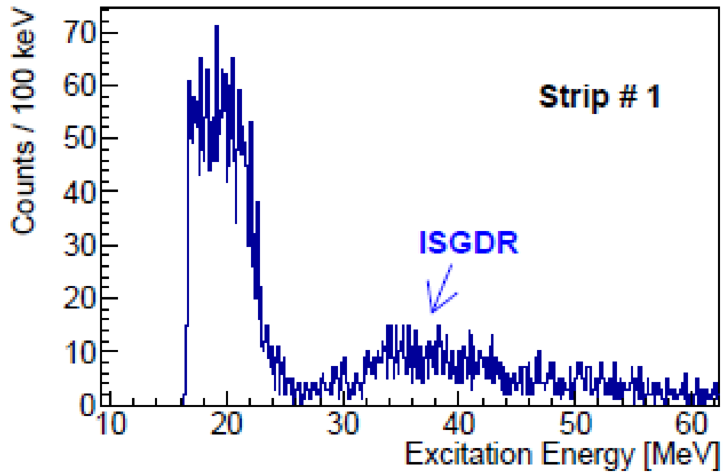
data down to Θ_{cm} < 1 deg !

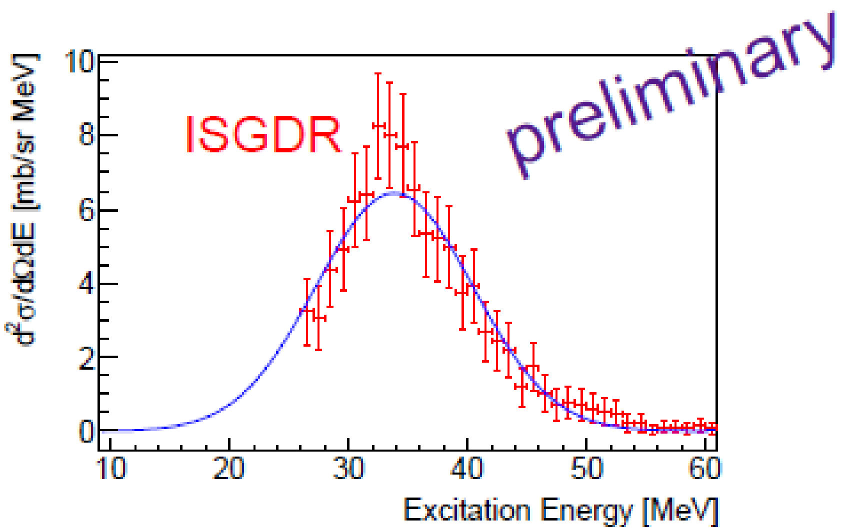
centroid [MeV]	EWSR [%]	
$22.2^{+1.2}_{-1.8}$	86^{+15}_{-13}	present data
$21.5^{+3.0}_{-0.3}$	74^{+22}_{-12}	PRC **61**, 067307 (2000)
$20.8^{+0.9}_{-0.3}$	85^{+13}_{-10}	PRC **73**, 014314 (2006)
22.0	108	RPA calculation [3]

[3] G. Colò et al, Comput. Phys. Commun. 184 (2013)

J. C. Zamora et al., to be published

Investigation of the Isoscalar Dipole Resonance in ^{58}Ni





Centroid [MeV]	
33.9(5)	present data
34.1(3)	PRC **73**, 014314 (2006)
$30.8^{+1.7}_{-1.1}$	Phys. Lett. B **637**, 43 (2006)

RMS-width [MeV]	
7.1(6)	present data
8.3(2)	PRC **73**, 014314 (2006)

Future Perspectives

short term perspectives:

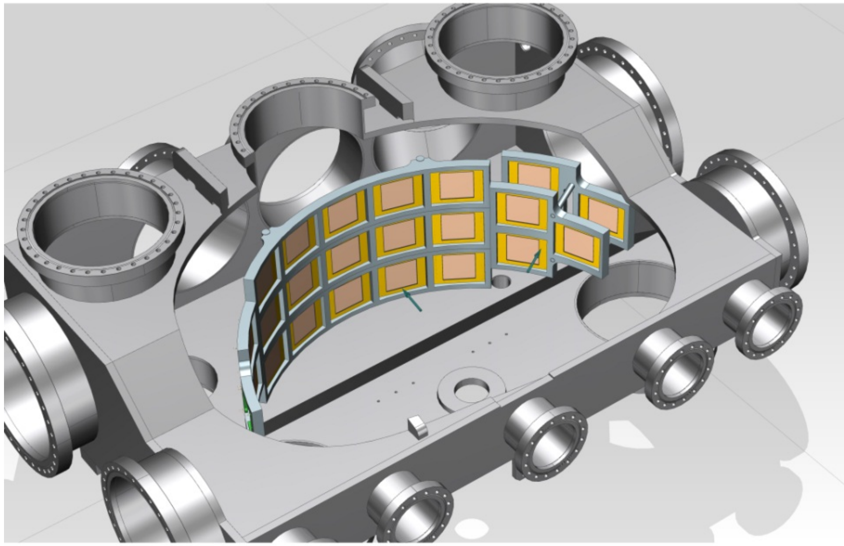
- (α,α`) on ^{56}Ni ⇒ investigate ISGMR and ISGDR
  ⇒ investigate the compressibility of nuclear matter

Future Perspectives

short term perspectives:

- (α,α`) on ^{56}Ni ⇒ investigate ISGMR and ISGDR

  needs upgrade of detector setup and readout (ASICS)



- (^{3}He,t) on ^{56}Ni ⇒ investigate Gamow – Teller strength

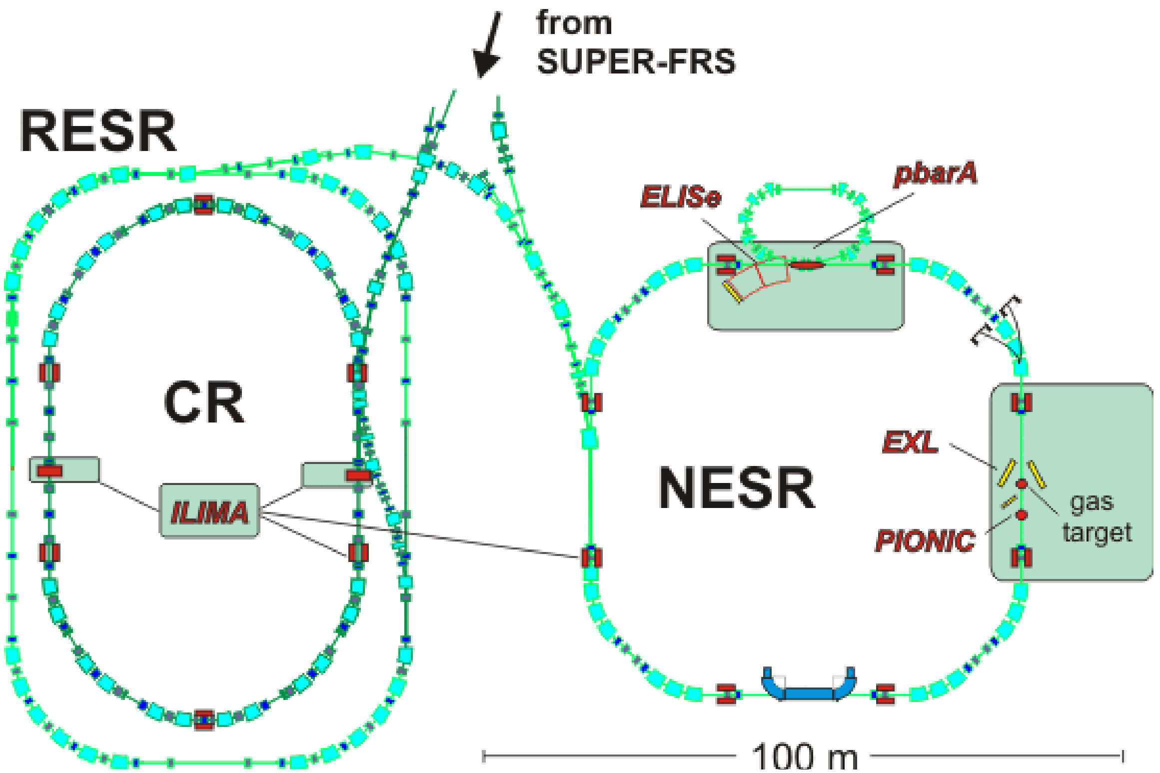
  needs upgrade of internal target

- transfer reactions at Cryring (GSI) and TSR@ISOLDE (CERN)

Future Perspectives

long term perspectives (EXL @ FAIR):

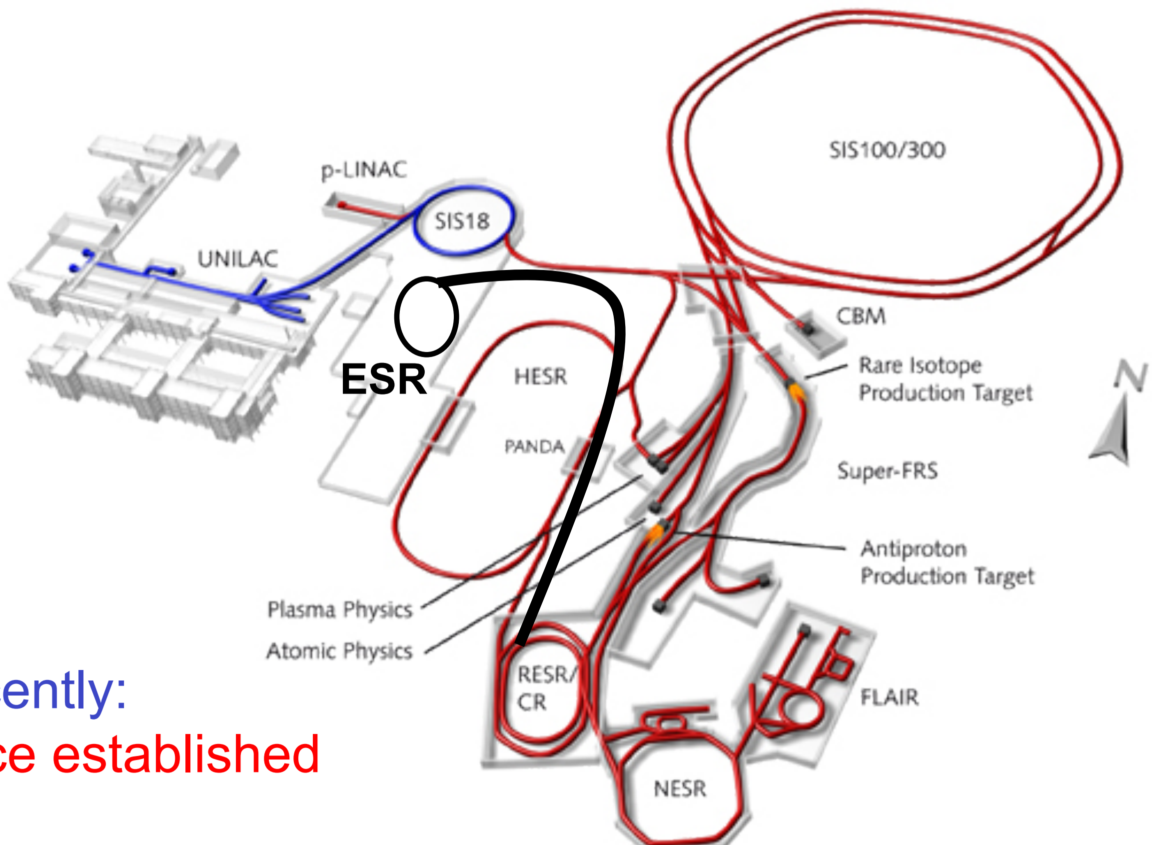
- still first priority:
  EXL at the NESR (full performance of EXL)



Future Perspectives

long term perspectives (EXL @ FAIR):

- for first phase of FAIR:
  transfer line from SUPER-FRS / CR to the ESR



- very recently:
  task force established

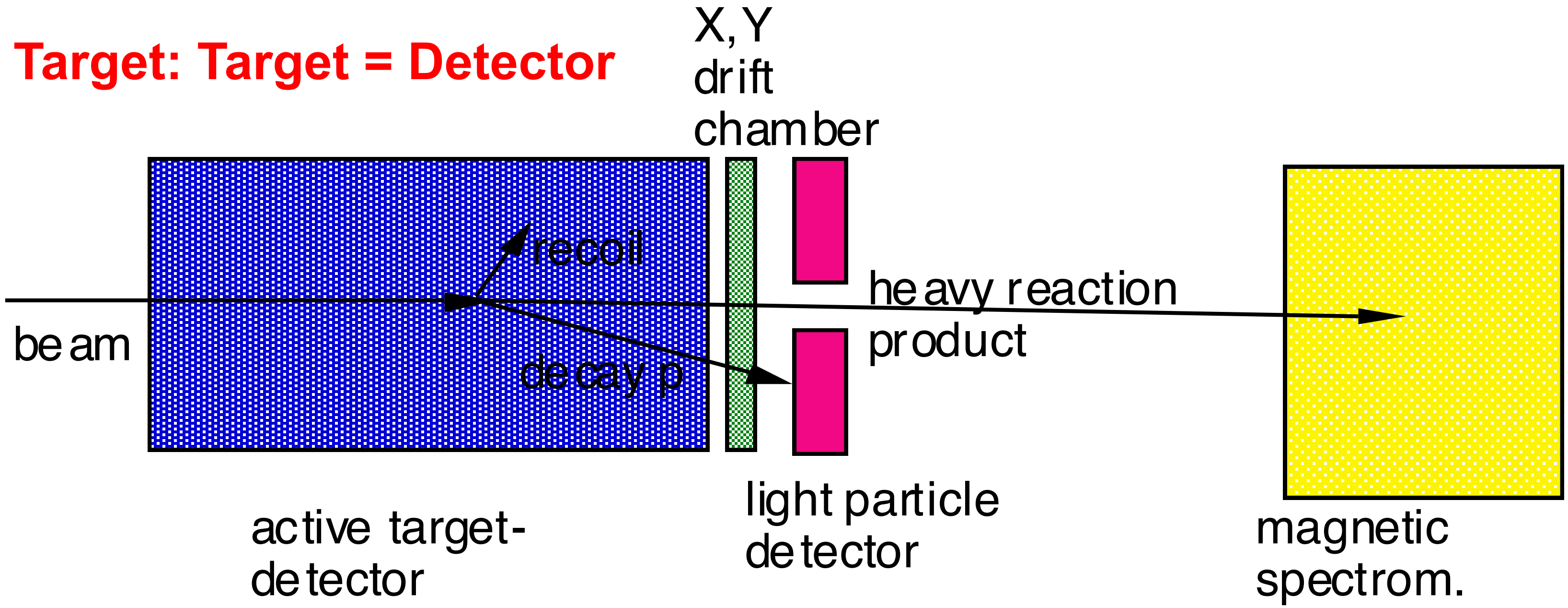
The E105 Collaboration

S. Bagachi[1], S. Bönig[2], M. Castlós[3], I. Dillmann[4], C. Dimopoulou[4], P. Egelhof[4], V. Eremin[5], H. Geissel[4], R. Gernhäuser[6], M.N. Harakeh[1], A.-L. Hartig[2], S. Ilieva[2], N. Kalantar−Nayestanaki[1], O. Kiselev[4], H. Kollmus[4], C. Kozhuharov[4], A. Krasznahorkay[3], T. Kröll[2], M. Kuilman[1], S. Litvinov[4], Yu.A. Litvinov[4], M. Mahjour-Shafiei[1], M. Mutterer[4], D. Nagae[8], M.A. Najafi[1], C. Nociforo[4], F. Nolden[4], U. Popp[4], C. Rigollet[1], S. Roy[1], C. Scheidenberger[4], M. von Schmid[2], M. Steck[4], B. Streicher[2,4], L. Stuhl[3], M. Takechi[4], M. Thürauf[2], T. Uesaka[9], H. Weick[4], J.S. Winfield[4], D. Winters[4], P.J. Woods[10], T. Yamaguchi[11], K. Yue[4,7], J.C. Zamora[2], J. Zenihiro[9]

[1] **KVI, Groningen**
[2] **Technische Universität Darmstadt**
[3] **ATOMKI, Debrecen**
[4] **GSI, Darmstadt**
[5] **Ioffe Physico-Technical Institute, St.Petersburg**
[6] **Technische Universität München**
[7] **Institute of Modern Physics, Lanzhou**
[8] **University of Tsukuba**
[9] **RIKEN Nishina Center**
[10] **The University of Edinburgh**
[11] **Saitama University**

III. Direct Reactions with Active Targets

Active Target: Target = Detector



⇒ advantage:

- low threshold
- high detection efficiency (rel. thick target)

⇒ well suited as alternative technique to EXL for:

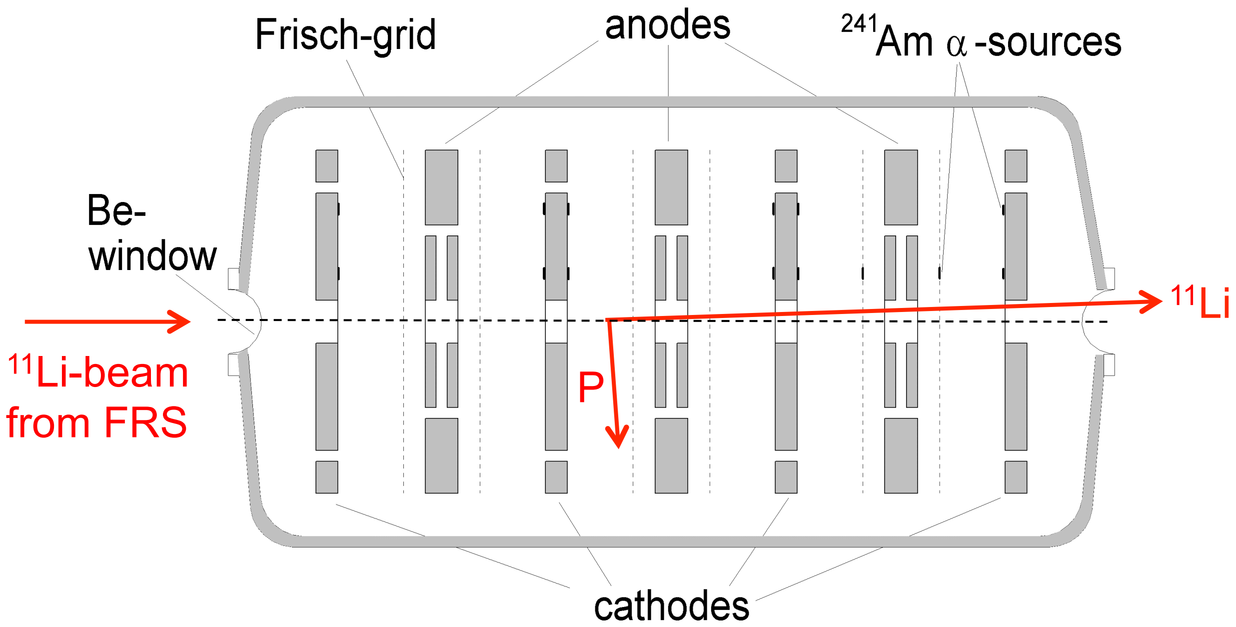
- short lifetimes (T ≤ 1 sec)
- low RIB intensities (≤ 10^4 sec^{-1})

III.1. Experimental Concept: The TPC-Ionization Chamber IKAR as Active Target

(provided by PNPI St. Petersburg)

detection principle:

H_2-target = detector for recoil protons (from elastic scattering)

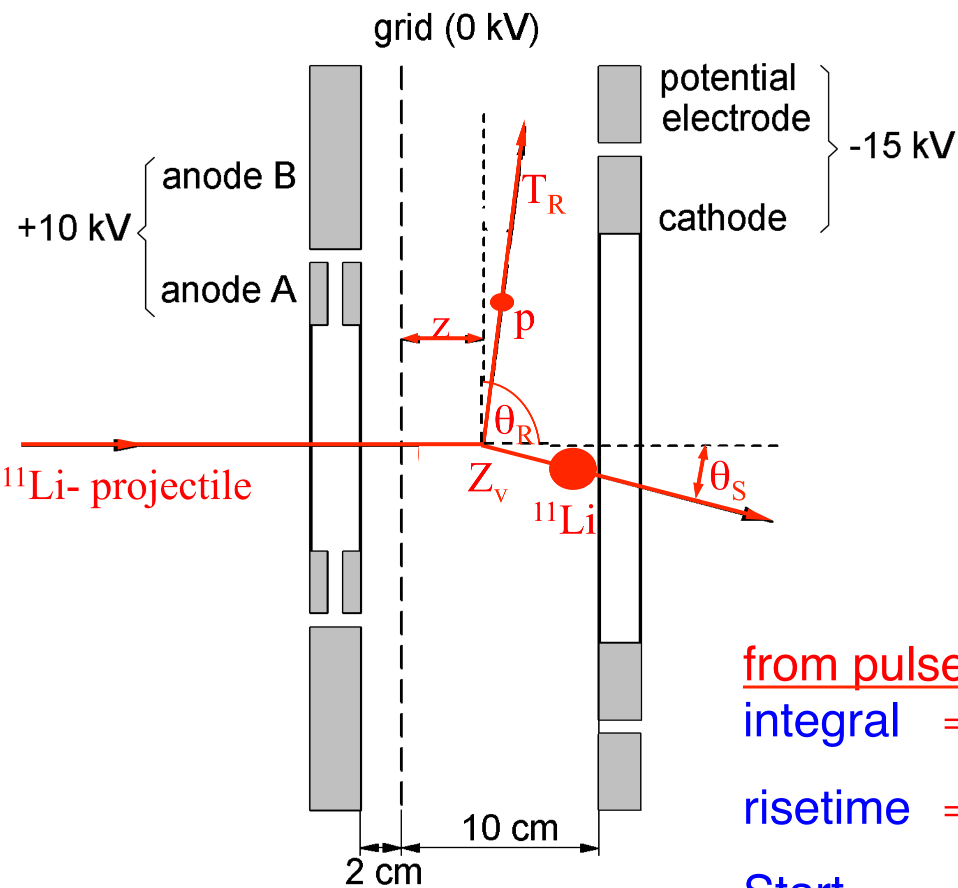


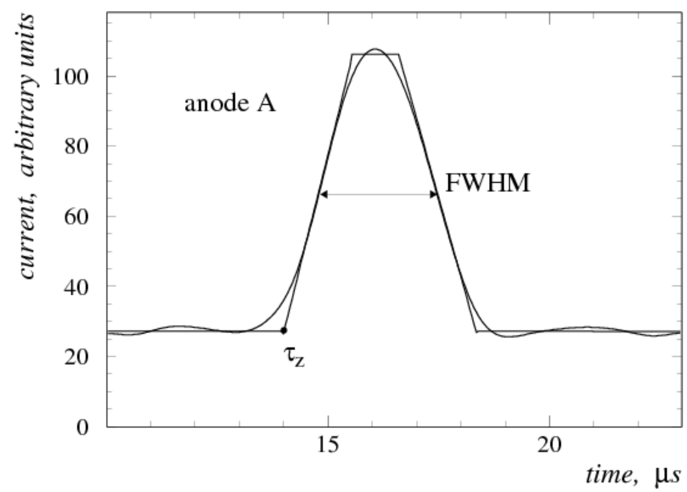
operating conditions:

H_2-pressure:	10 atm
entrance window:	0.5 mm Berylium
target thickness:	30 mg/cm² (6 independent sections)
beam rate:	$\leq 10^4$/sec

but: method limited to $Z \leq 6$!

Detection Principle of IKAR





from pulse analysis:

integral ⇒ recoil energy T_R ($\Delta E_{FWHM} \leq 90$ KeV)

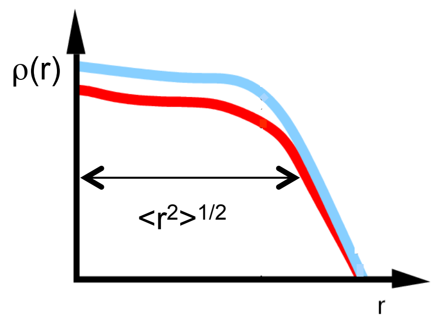
risetime ⇒ recoil angle θ_R ($\Delta\theta_{FWHM} \leq 0.6°$)

Start ⇒ vertex point Z_V ($\Delta z_{FWHM} \leq 110$ μm)

III.2. Small Angle Elastic Proton Scattering - a Tool to Study the Radial Shape of Exotic Nuclei

The radial shape and size of nuclei is a basic nuclear property !

⇒ of high interest for nuclear structure physics



observables: nuclear charge distribution: $\rho_{ch}(r)$, $<r_{ch}^2>^{1/2}$ ⇨ leptonic probes

nuclear matter distribution: $\rho_m(r)$, $<r_m^2>^{1/2}$ ⇨ hadronic probes

method: intermediate energy elastic proton scattering

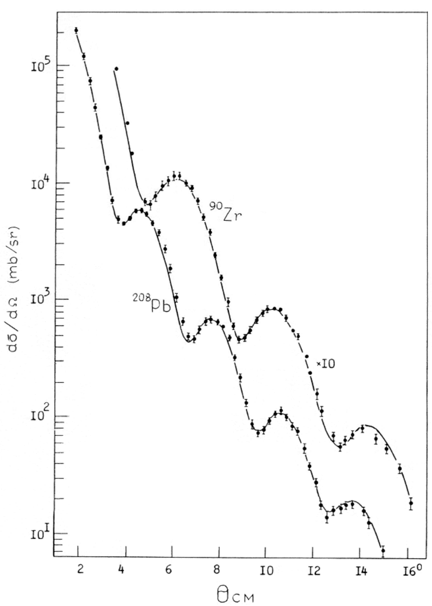
⇒ well established method for determination of nuclear matter distributions (of stable nuclei)

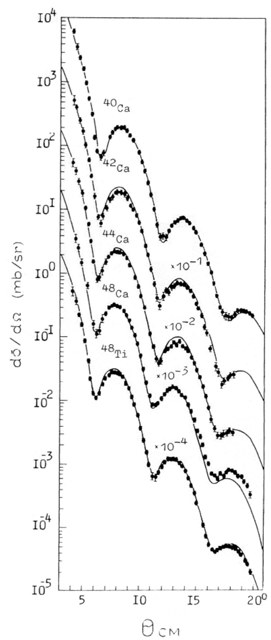
⇒ what about exotic nuclei?

Elastic Proton Scattering at Intermediate Energies around 1 GeV/u

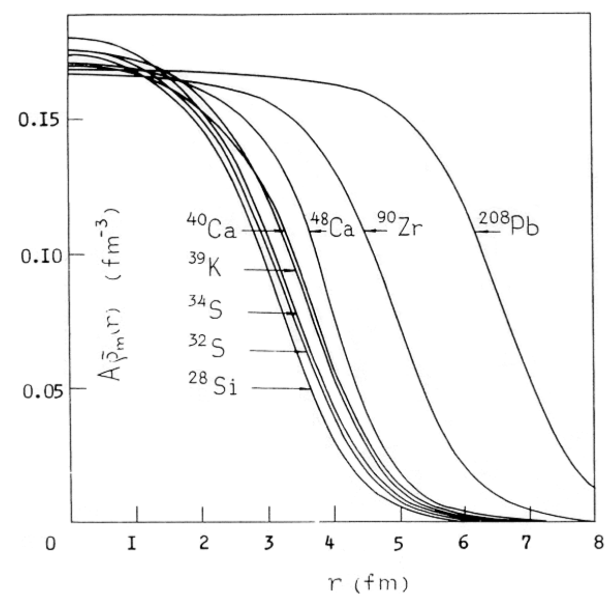
well established method to investigate nuclear matter distributions of stable nuclei (see G. Alkhazov et al., Phys. Rep. 42 (1978) 89)

measured cross sections





deduced nuclear matter distributions

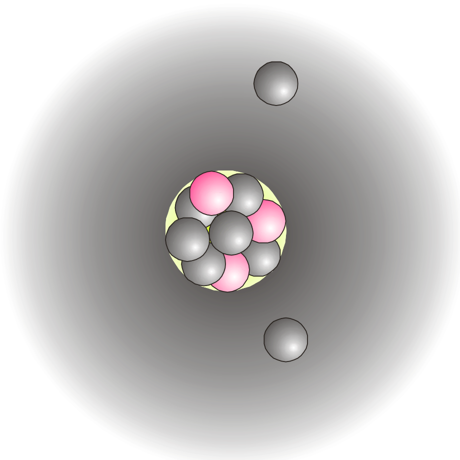


with radioactive beams ⇒ application to exotic nuclei

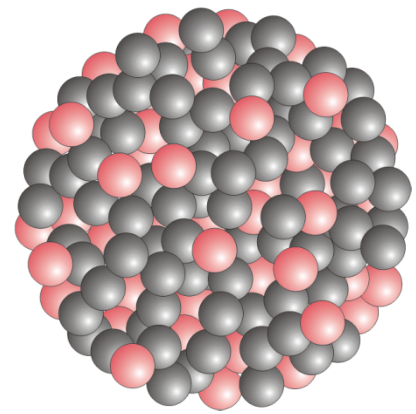
Halo-Nuclei – a New Phenomenon of the Structure of Nuclei

Density Distribution of Nuclear Matter

^{11}Li



^{208}Pb



extremely neutron-rich nuclei:

neutron halo

stable nuclei:

neutrons and protons equally distributed

Intermediate Energy Elastic Proton Scattering - a Tool to Study the Radial Shape of Halo Nuclei

aim: quantitative information on the nuclear matter distributions

method: intermediate energy (700 – 1000 MeV) elastic proton scattering

of special interest: light isotopes with halo-structure: ^{6}He, ^{8}He, ^{11}Li, ^{14}Be, ^{8}B, ^{17}C(?)

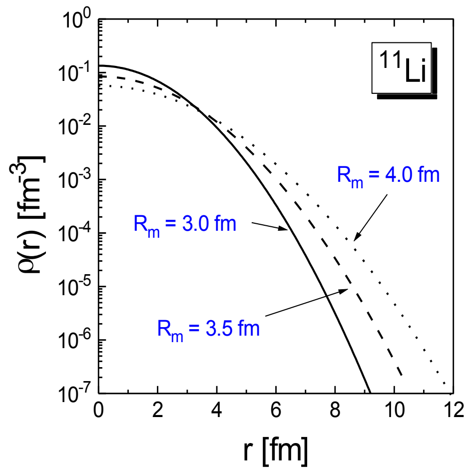
for low momentum transfer:

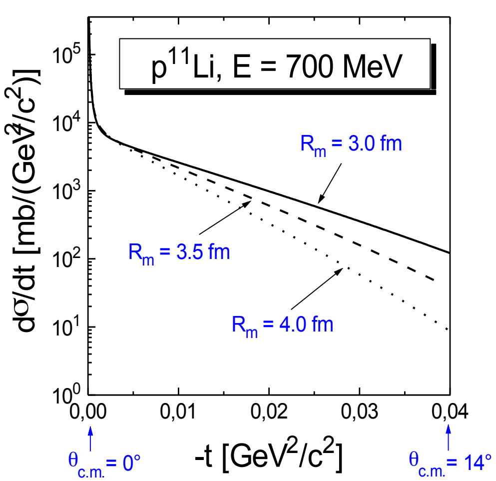
high sensitivity on the halo structure

⇒ determination of matter radii

⇒ determination of the radial shape of the nuclear matter distribution

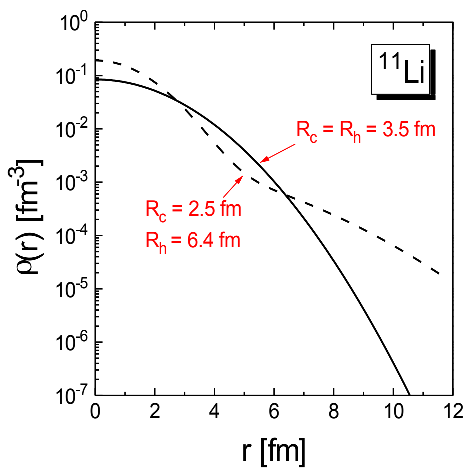
Sensitivity of Elastic Proton Scattering on the Radial Shape of the Nuclear Matter Distribution

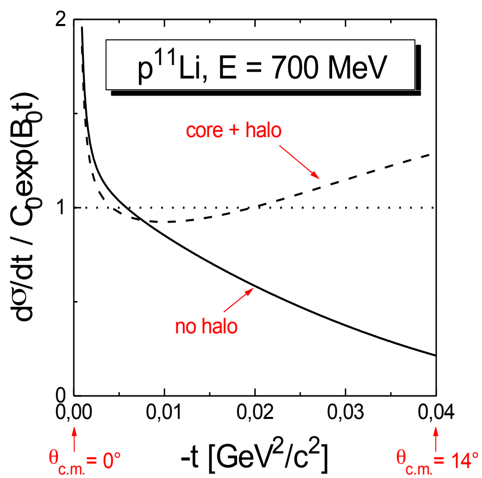




slope of $d\sigma/dt$

→ matter radius R_m



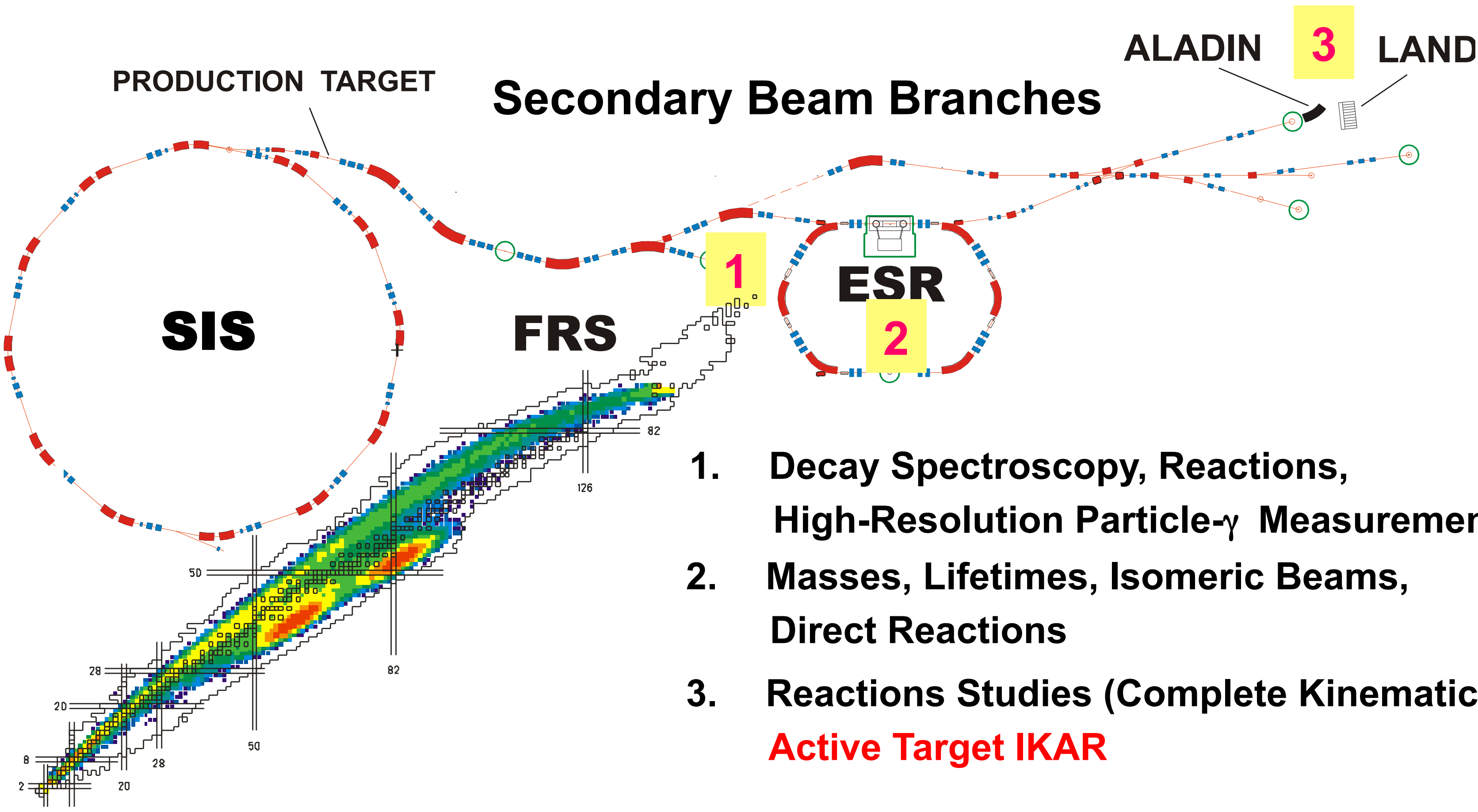


curvature of log ($d\sigma/dt$)

→ halo structure

The Present Radioactive Beam Facility at GSI

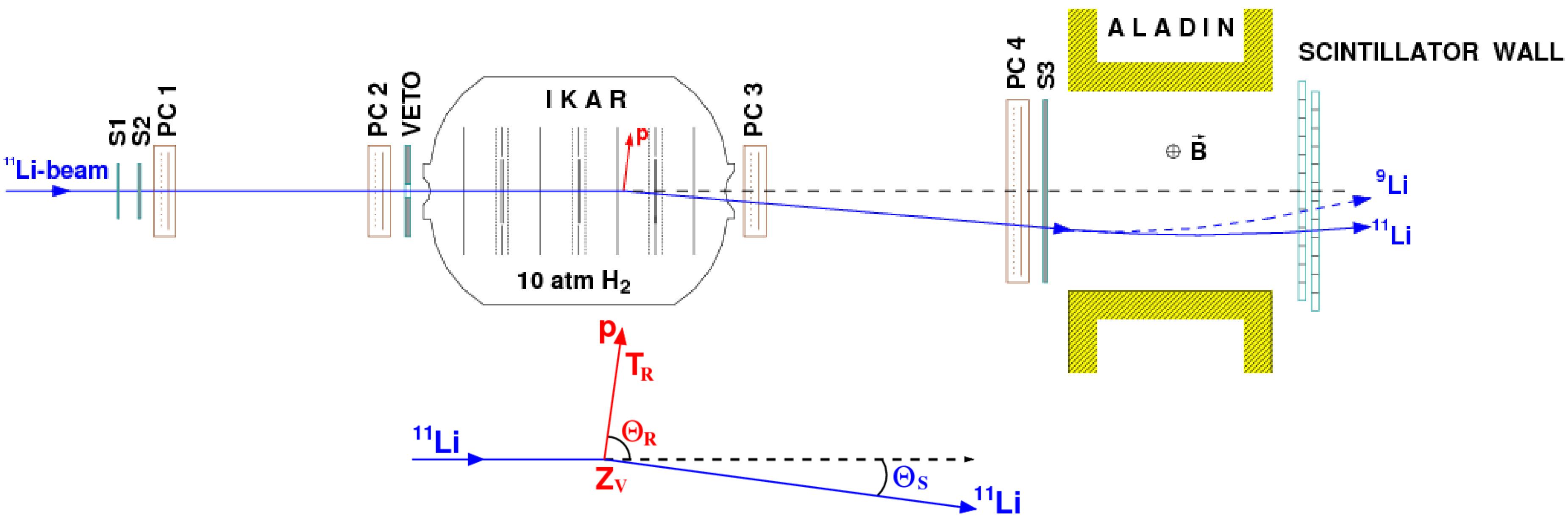
FRS: In-Flight Separator & High-Resolution Spectrometer



1. Decay Spectroscopy, Reactions, High-Resolution Particle-γ Measurements
2. Masses, Lifetimes, Isomeric Beams, Direct Reactions
3. Reactions Studies (Complete Kinematics) Active Target IKAR

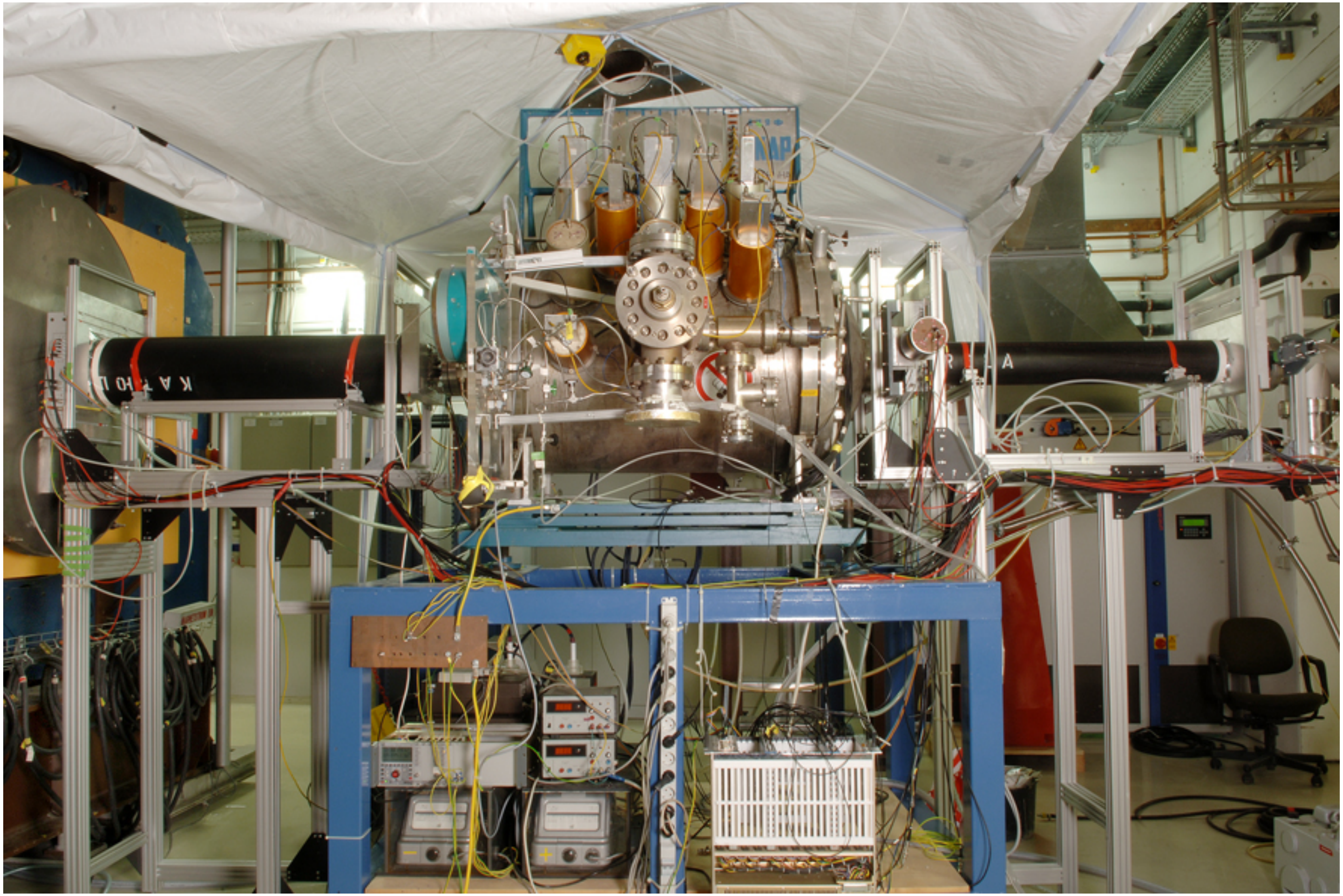
Investigation of Nuclear Matter Density Distributions of Halo Nuclei by Elastic Proton Scattering

Experimental Setup: Active Target IKAR and Aladin Magnet



target + recoil detector:	IKAR	} ⇒ T_R, θ_R, Z_V
trajectory-reconstruction:	PC 1-4 (Multiwire proportional chambers)	} ⇒ θ_S
beam identification:	S 1-3, Veto (plastic scintillators)	} ⇒ ΔE, TOF, trigger
	ALADIN-magnet + position sensitive scintillator wall	} ⇒ discrimination of projectile breakup

The IKAR Experimental Setup



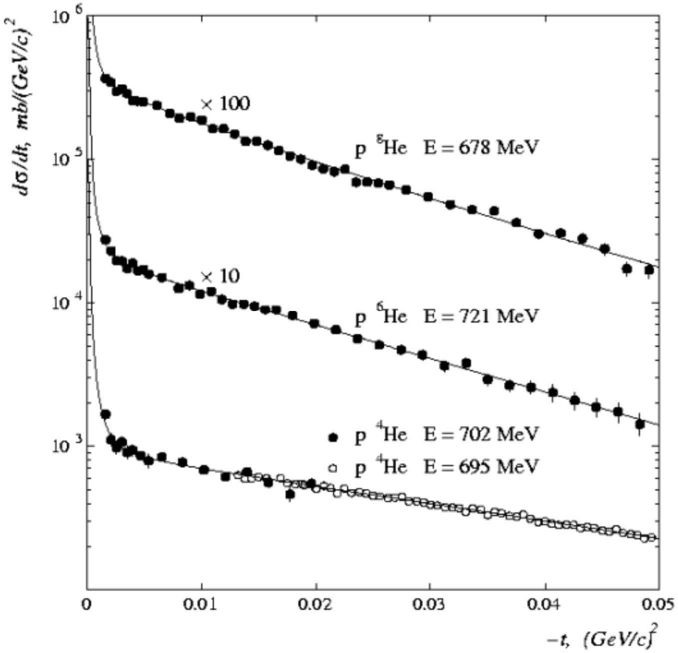
Investigation of Nuclear Matter Density Distributions of Halo Nuclei by Elastic Proton Scattering at Low Momentum Transfer

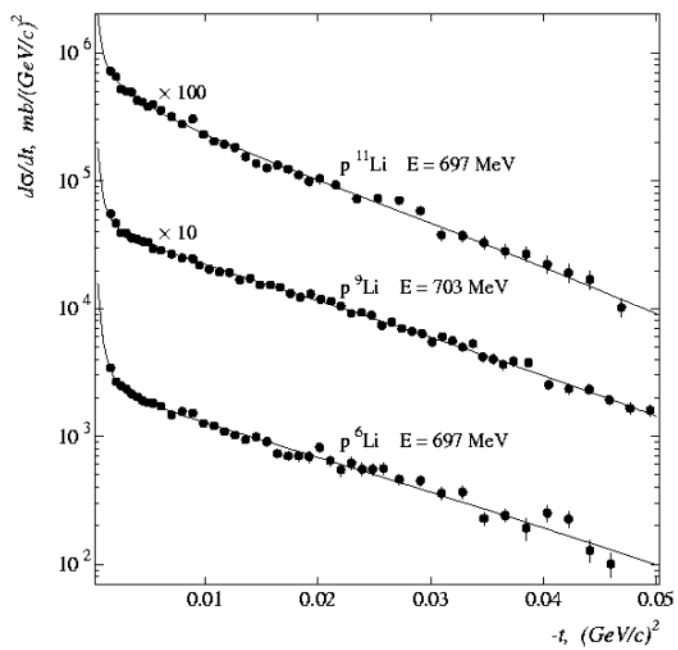
S. R. Neumaier et al.,Nucl. Phys. A 712 (2002) 247

G. D. Alkhazov et al., Nucl. Phys. A 712 (2002) 269

P. Egelhof et al., Eur. Phys. J. A 15 (2002) 27

A. Dobrovolsky et al., Nucl. Phys. A766 (2006) 1





Θ_{cm} = 12°

Θ_{cm} = 16°

all experimental data are well described by Glauber calculations

Concept of the Data Analysis

- Glauber multiple-scattering theory for calculation of cross sections:
  - use measured free pp, pn-cross sections as input (in medium effects negligible)
  - fold with nucleon density distribution
  - take into account multiple scattering (all terms!) (small for region of nuclear halo!)

- variation of the nucleon density distribution:

  a) phenomenological parametrizations (point matter densities):

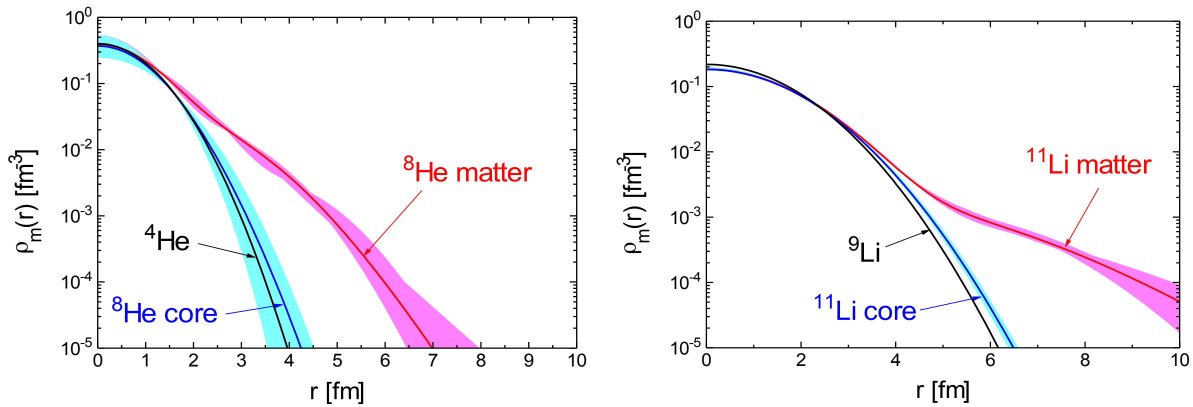
  G: 1 Gaussian
  SF: Symmetrized Fermi
  GG: 2 Gaussians
  GO: Gaussian + Harmonic Oscillator

  b) "model independent" analysis:

  SOG: Sum Of Gaussians
  (standard method for electron scattering data:
  I. Sick, Nucl. Phys. A 218 (1974) 509)

Investigation of Nuclear Matter Density Distributions of Halo Nuclei by Elastic Proton Scattering at Low Momentum Transfer

nuclear matter distributions:



nuclear matter radii:

nucleus	R_{matter}, fm	R_{core}, fm	R_{halo}, fm
^{4}He	1.49 (3)	--	--
^{8}He	2.53(8)	1.55 (15)	3.22 (14)
^{9}Li	2.44 (6)	--	--
^{11}Li	3.71 (20)	2.53 (3)	6.85 (58)

- extended neutron distribution in ^{8}He and ^{11}Li obtained
- size of core, halo and total matter distribution determined with high accuracy
- the picture of a ^{9}Li (^{4}He) core + 2 (4) valence neutron-structure is confirmed for ^{11}Li and ^{8}He

Determination of Neutron Radii and Neutron Skin Sizes

- needs input on proton (charge) distributions

  ⇒ use data from laser spectroscopy (isotope shift measurements):

  for ^{6}He: L.-B. Wang et al., PRL 93, 142501 (2004)

  for $^{8,9,11}Li$: R. Sanchez et al., PRL 96, 033002 (2006)

  M. Puchalski et al., PRL 97, 1330016 (2006)

- neutron radius:

$$R_n^{\ 2} = \frac{1}{N_n} * \left(A R_m^{\ 2} - N_p R_p^{\ 2} \right)$$

- neutron skin size:

$$\delta_{np} = R_n - R_p$$

Summary of all Data on Nuclear Radii

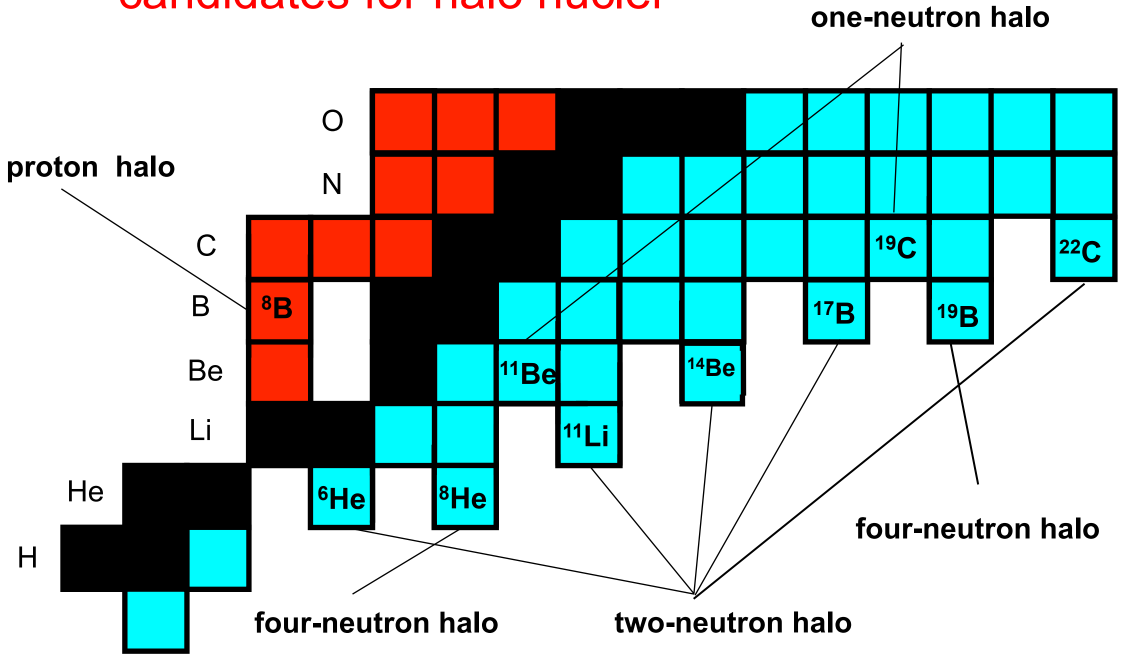
nucleus	R_m, fm	R_{core}, fm	R_{halo}, fm	R_p*, fm	R_n, fm	δ_{np}, fm
^{6}He	2.45 (10)	1.88 (12)	3.31 (28)	1.91 (2)	2.60 (7)	0.69 (7)
^{8}Li	2.50 (6)	--	--	2.15 (3)	2.69 (9)	0.54 (10)
^{9}Li	2.44 (6)	--	--	2.06 (4)	2.61 (9)	0.55 (10)
^{11}Li	3.71 (20)	2.53 (3)	6.85 (58)	2.33(4)	3.75 (15)	1.42 (16)

* R_p from laser spectroscopy, unfolded from proton charge radius

Recent Results on Halo Structures in Exotic Be, B, and C Isotopes

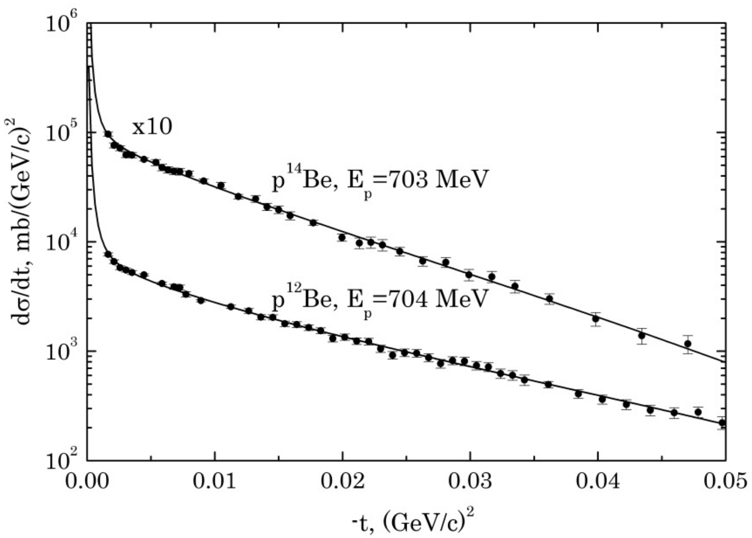
- two experiments with primary ^{12}C and ^{18}O beams were successfully performed
- data on ^{12}Be, ^{14}Be and ^{8}B, ^{15}C, ^{17}C were taken: S.Ilieva et al., S. Tang et al.

candidates for halo nuclei

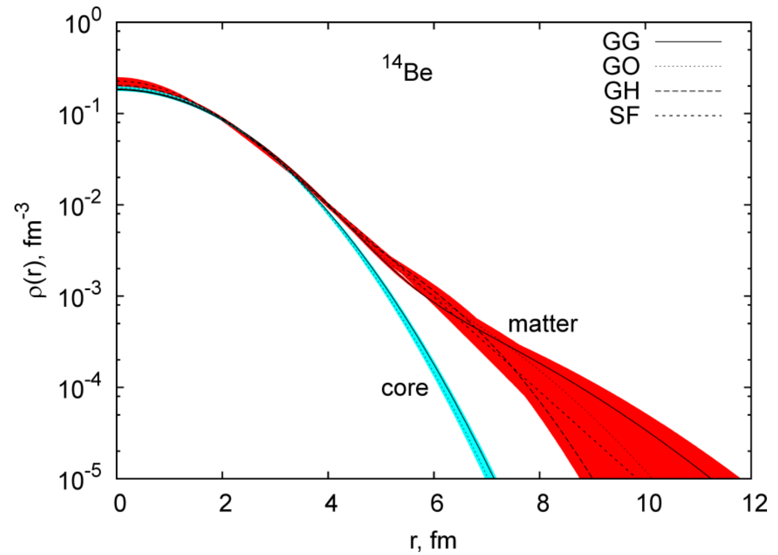


Elastic Proton Scattering from ^{14}Be

differential cross section:



deduced nuclear matter distribution:



S. Ilieva et al.,
Nucl. Phys. A 875 (2012) 8

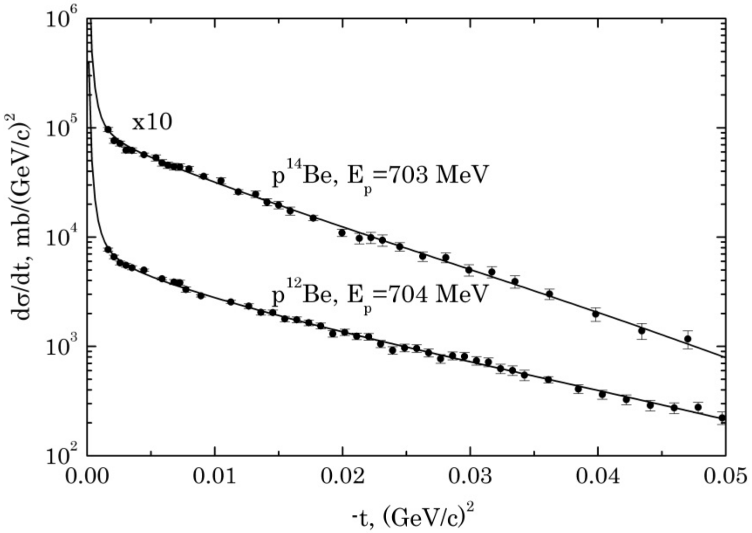
results for ^{14}Be:

R_{matter} = 3.25 ± 0.04 ± 0.11 fm
R_{core} = 2.65 ± 0.02 ± 0.11 fm

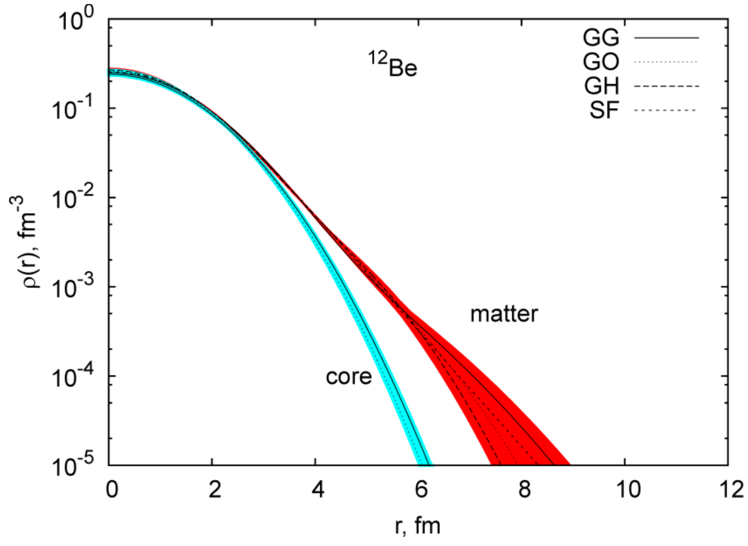
- ^{14}Be exhibits a pronounced core-halo structure
- the picture of a ^{12}Be-core + 2 valence neutron structure is confirmed
- the present data favour a relatively large s-wave component
  (see I. Thompson et. al, Phys. Rev. C53 (1996) 708)

Elastic Proton Scattering from ^{12}Be

differential cross section:



deduced nuclear matter distribution:

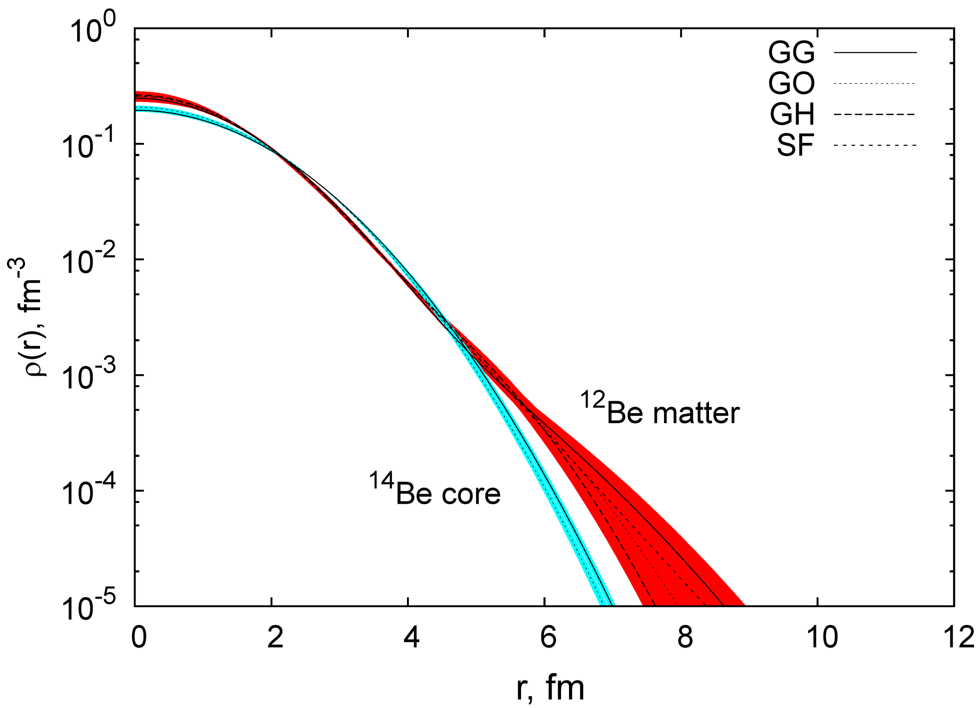


results for ^{12}Be:

R_{matter} = 2.71 ± 0.03 ± 0.06 fm
R_{core} = 2.17 ± 0.02 ± 0.09 fm

- ^{12}Be exhibits an extended matter distribution
- the contribution of (sd) intruder states is confirmed
  (see I. Thompson et al., Phys. Rev. C53 (1996) 703)

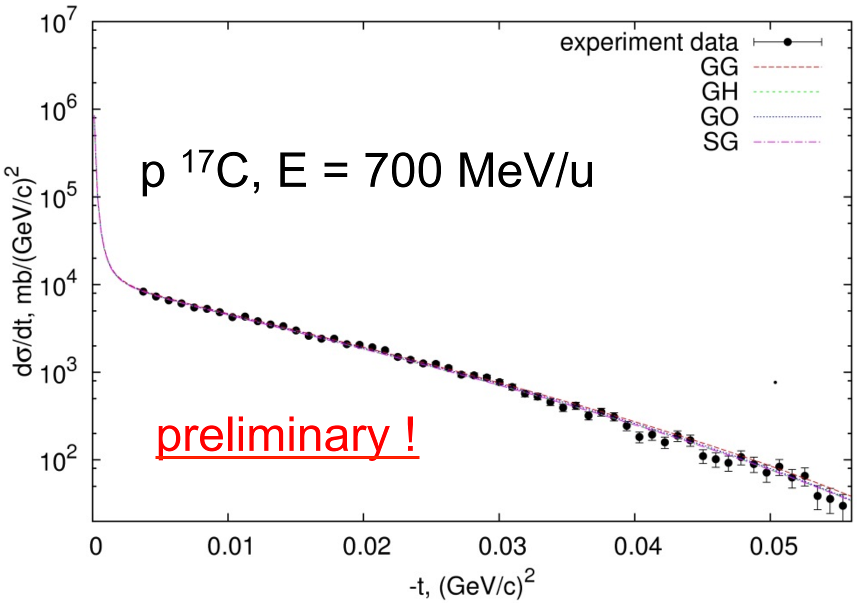
Comparison of the ^{14}Be core with the free ^{12}Be



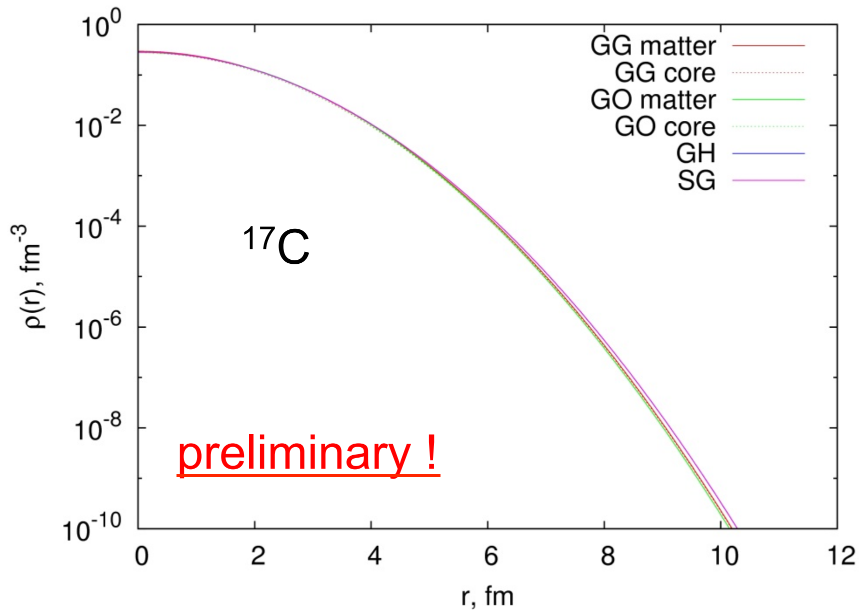
- the free ^{12}Be nucleus exhibits a different structure as compared to the core in ^{14}Be
  ⇒ may be explained by different shell occupation of last 2 neutrons (p or sd)

Elastic Proton Scattering from ^{17}C

differential cross section:



deduced nuclear matter distribution:



S. Tang et. al,
to be published

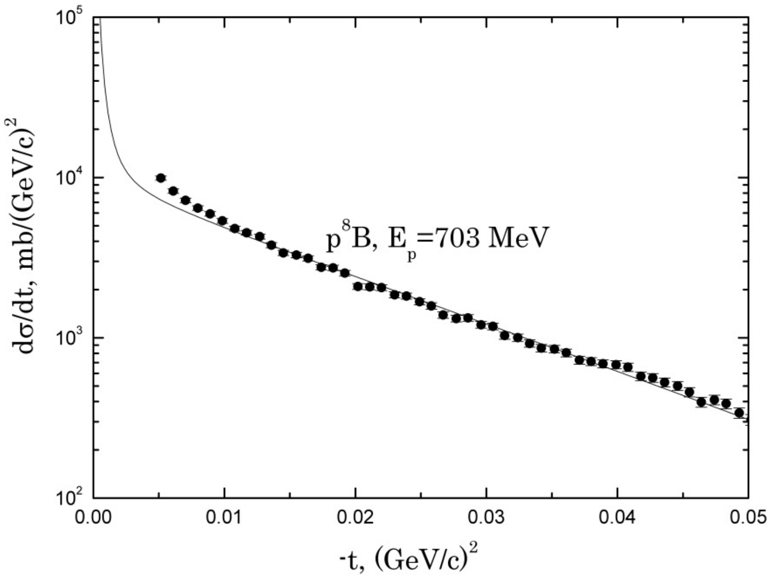
results for ^{17}C:

R_{matter} = 2.70 ± 0.02 ± 0.10 fm

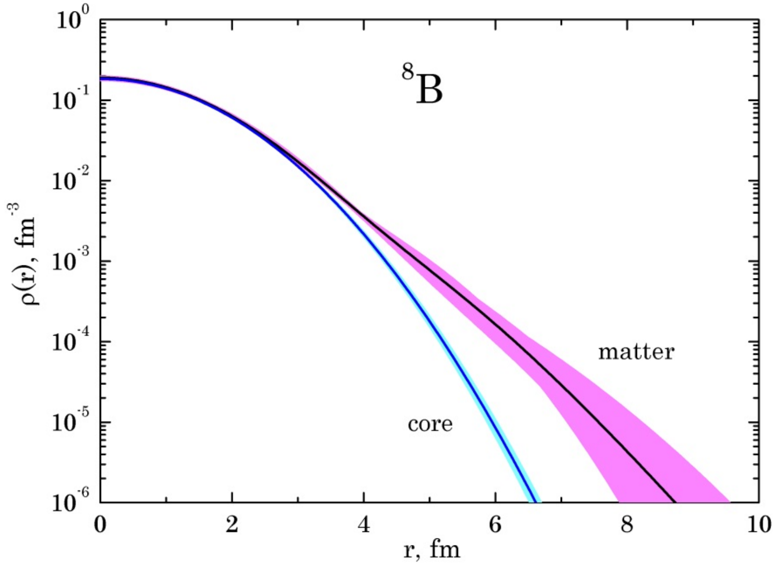
- for ^{17}C no evidence for an extended matter distribution (or halo structure) is observed
- indication for dominant d-wafe contribution
- in agreement with A. Ozawa et al., Nucl. Phys. A691 (2001)599: R_m = 2.72 (0,04) fm
- partly in disagreement with C. Wu et al., Nucl. Phys. A739(2004)3

Elastic Proton Scattering from ^{8}B

differential cross section:



deduced nuclear matter distribution:



A. Inglesi et. al,
to be published

- for the first time a proton halo was investigated
- the halo structure of ^{8}B was confirmed
- the deduced matter radius R_m = 2.60 ± 0.04 ± 0.20 fm is in agreement with previous results and theoretical predictions (R_m = 2.4 -2.6 fm)
- relevance for the astrophysical S(E) factor for the $^{7}Be(p,\gamma)^{8}B$ reaction ?

  ⇒ to be investigated !!!

The IKAR-Collaboration

F. Aksouh, G.D. Alkhazov, M.N. Andronenko, L. Chulkov, A.V. Dobrovolsky, P. Egelhof, H. Geissel, M. Gorska, S. Ilieva, A. Inglessi, A.V. Khanzadeev, O. Kiselev, G.A. Korolev, C. L. Le, Y. Litvinov, G. Münzenberg, M. Mutterer, S.R. Neumaier, C. Nociforo, C. Scheidenberger, L. Sergeev, D.M. Seliverstov, H. Simon, S. Tang, N.A. Timofeev, A.A. Vorobyov, V. Volkov, H. Weick, V.I. Yatsoura, A. Zhdanov

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Kurchatov Institute, Moscow, Russia
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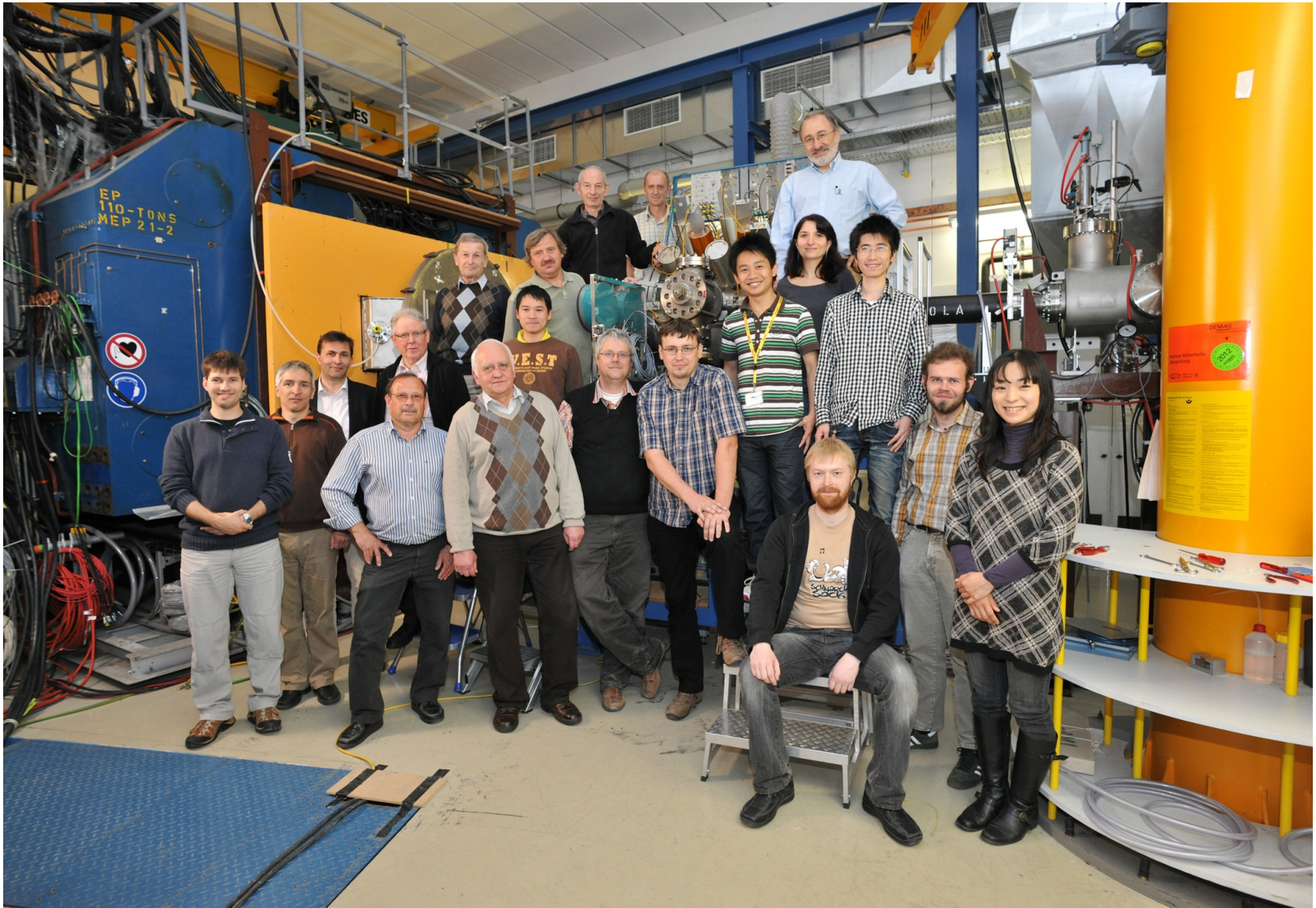
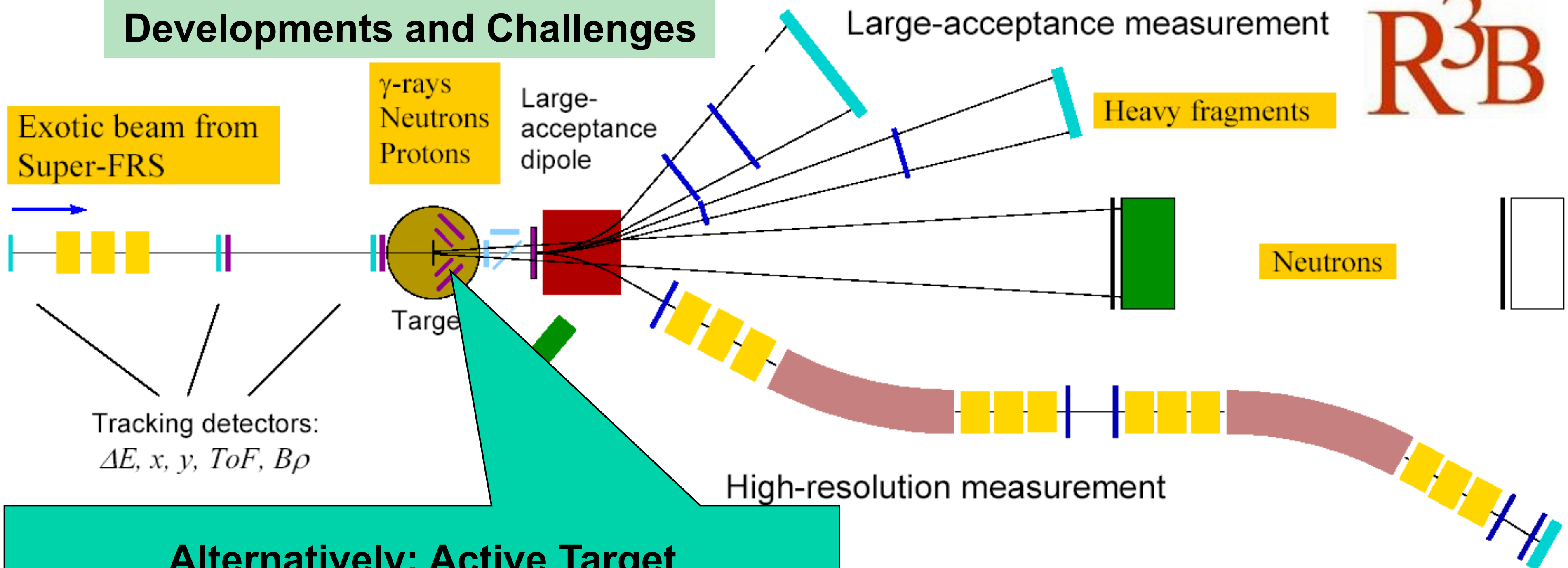
Institut für Kernphysik, TU Darmstadt, Darmstadt, Germany

The IKAR Collaboration



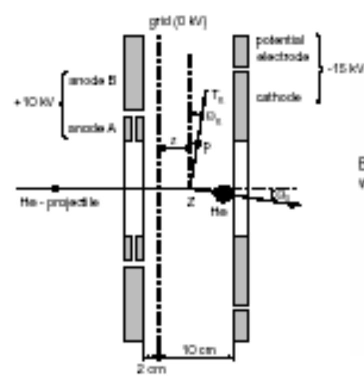
Future Perspectives @ FAIR:
R3B: Reactions with Relativistic Radioactive Beams

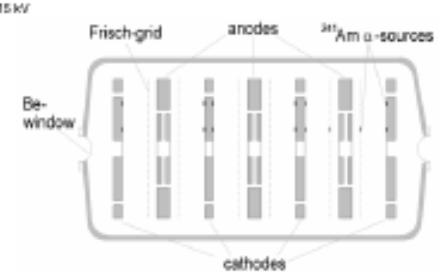
Developments and Challenges



Alternatively: Active Target

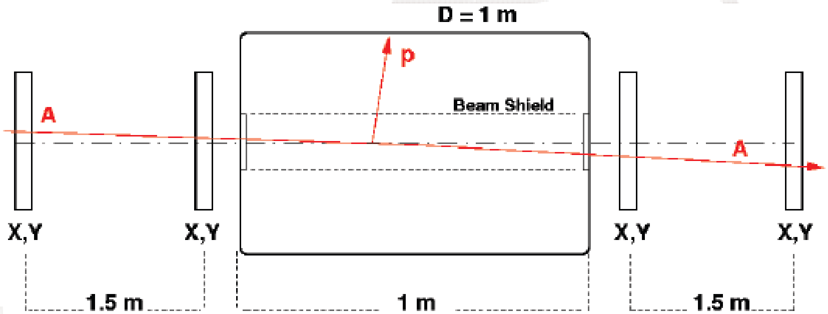
measurement of recoils in reactions with low-momentum transfer

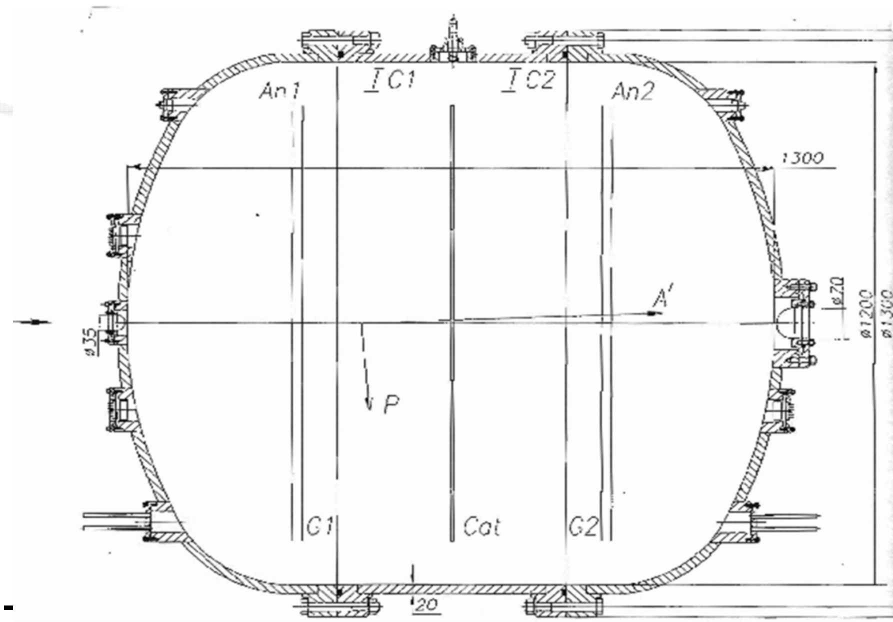




A New Active Target for R^3B @ FAIR

Active Target for R3B - design





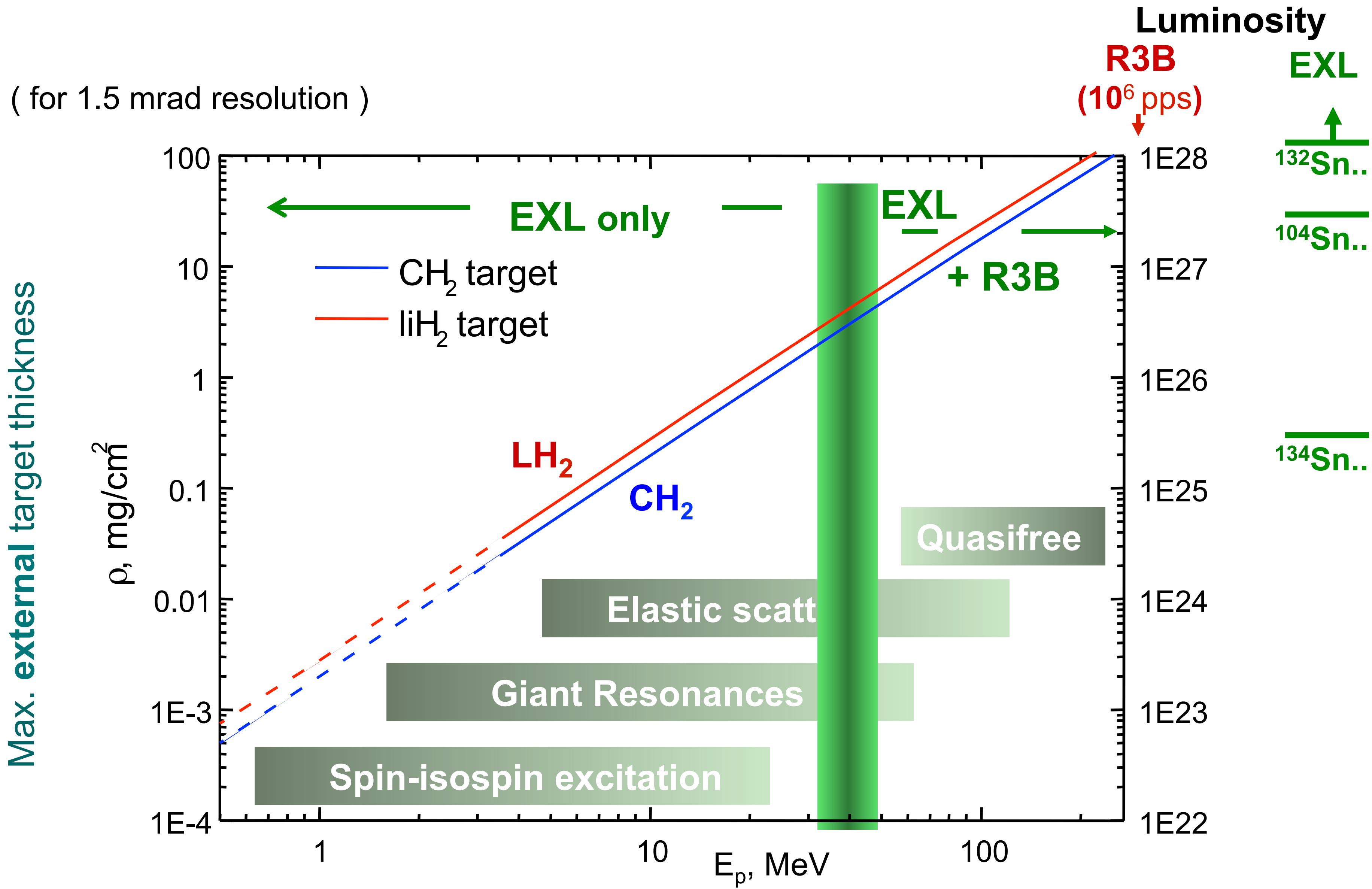
- Modified version of IKAR chamber
- Beam shielding anode ∅ 2 cm
- Gas – H_2, D_2, ^3He, ^4He, CH_4, Ar
- Pressure – up to 25 bar

Effective target length – 40 cm
Effective target thickness – $4*10^{22}$ cm-
Luminosity ($I = 10^4$ s^{-1}) – $4*10^{26}$ $cm^{-2}s^{-1}$
$E_p(max)$ = 15 MeV, t_{max} = 0.03 $(GeV/c)^2$ (H_2, 25 bar)
A TDR is presently prepared.

IV. Conclusions

- For the First Time (World Wide) a Nuclear Reaction Experiment with Stored Radioactive Beams was successfully performed. .
- A number of Important Physics Questions can be only addressed with the EXL Technique which is up to date World Wide unique.
- The Active Target Technique is well suited for addressing very short lived nuclei, not accessible by EXL.
- Elastic Proton Scattering at Intermediate Energies is a powerful tool to study nuclear matter distributions in nuclei. The combination with data on the charge distribution allows to investigate the Size of Neutron Skins.
- The Future Facility NuSTAR@ FAIR will allow to reach Unexplored Regions in the Chart of Nuclei, where New and Exciting Phenomena are expected.
- EXL@FAIR and ACTAR@FAIR have a Large Potential for Nuclear Structure and Nuclear Astrophysics.

External Target Versus Internal Target



The EXL Collaboration

Univ. São Paulo
TRIUMF Vancouver
IMP Lanzhou
VTT Helsinki
IPN Orsay, CEA Saclay
GSI Darmstadt, TU Darmstadt, Univ. Frankfurt, FZ Jülich, Univ. Giessen, Univ. Mainz, Univ. Munich
INR Debrecen
SINP Kolkata, BARC Mumbai
KVI Groningen
INFN/Univ. Milano
Univ. Teheran
Univ. Osaka
JINR Dubna, PNPI Gatchina, KRI St. Petersburg, Ioffe Inst. St. Petersburg, Kurchatov Inst. Moscow
CSIC Madrid, Univ. Madrid
Univ. Lund, Mid Sweden Univ., Univ. Uppsala, Chalmers Inst. Göteborg
Univ. Basel
Univ. Birmingham, CLRC Daresbury, Univ. Surrey, Univ. York, Univ. Liverpool, Univ. Edinburgh
Tbilisi State University, Ilia Chavchavadze State University, Tbilisi, Georgia

Spokesperson: N. Kalantar (KVI)
Deputy: P. Egelhof (GSI)
GSI contact: H. Weick (GSI)
18 countries, 34 institutes, ~150 participants

Investigation of Gamow-Teller Transitions by Charge Exchange Reactions

GT strength can be extracted from charge exchange reactions, i.e. (^{3}He,t), (d,^{2}He), etc.

for E ≥ 100 MeV/u: $d\sigma/d\Omega dE$ (0°) ≈ $S(E_x) \cdot B(GT)$

⇨ important for several astrophysical scenarios:

- weak interaction rates for N = Z waiting point nuclei in the rp-process (^{72}Kr, ^{76}Sn, ^{80}Zn, ^{84}Mo, ^{88}Ru, ^{92}Pd, etc.)
- electron capture rates in the presupernova evolution (core collaps)

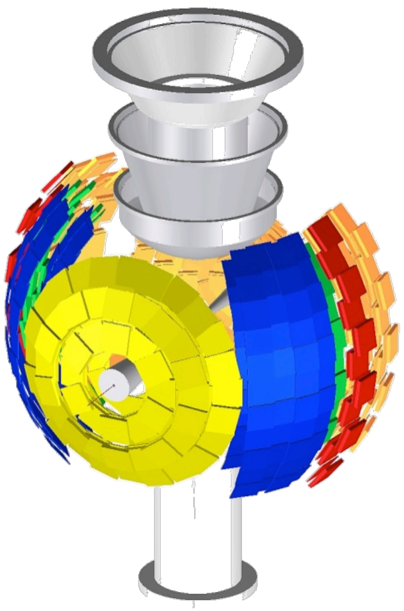
early phase:

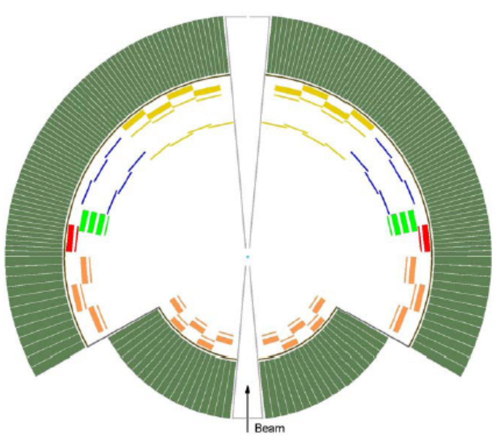
all radioactive isotopes within $^{55\text{-}60}$Co, $^{56\text{-}61}$Ni, $^{54\text{-}58}$Mn, $^{54\text{-}59}$Fe

later phase:

$e^- + (N,Z) \Leftrightarrow (N+1, Z-1) + \nu_e$ in equilibrium ⇨ neutron-rich Kr, Ge isotopes

Specifications of the Silicon Detectors for EXL

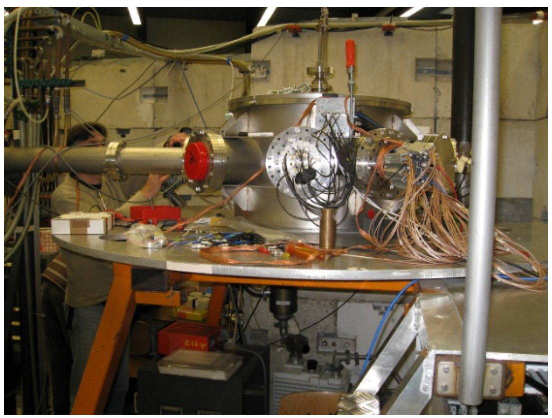




- low threshold ≤ 40 keV
  (⇒ constraints on thickness of entrance windows)
- high energy resolution ≤ 20 keV
- pitch size ≥ 0.5 mm
- active area 65 X 65 mm^2
- large dynamic range: 100 keV to 50 MeV
- readout of energy, time, PSA??
- self triggering
- moderate count rates
- UHV (HV) compatibility (partly)

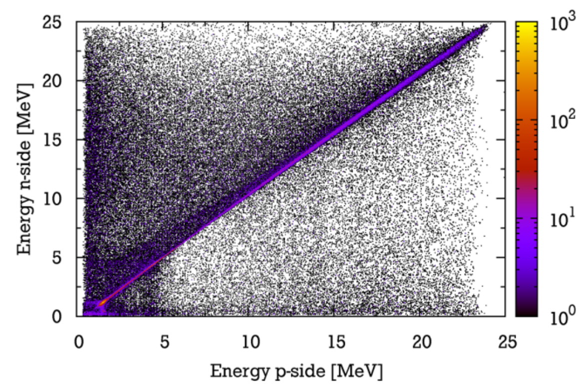
Pulse-Shape Discrimination with DSSD`s

test with p, d, ^{4}He from
^{12}C + ^{12}C @ 70 MeV
TU Munich

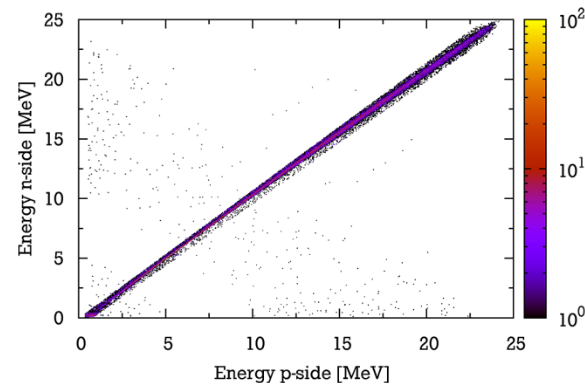


M. von Schmid et al.
NIM A629 (2011)197

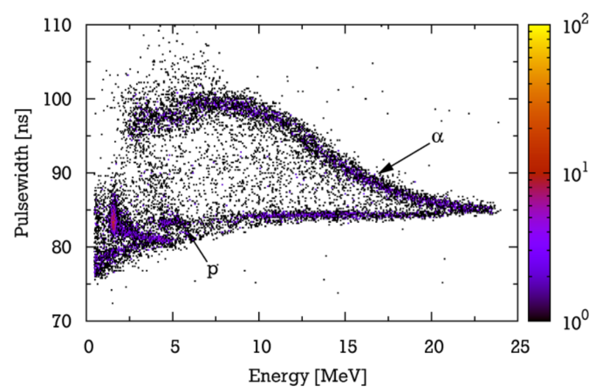
Strip & Interstrip

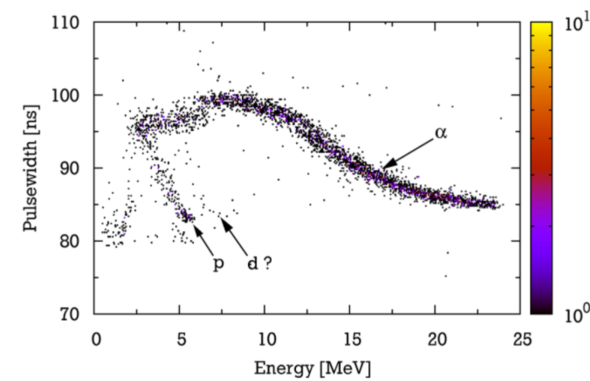


Strip (stopped α's)



P/N

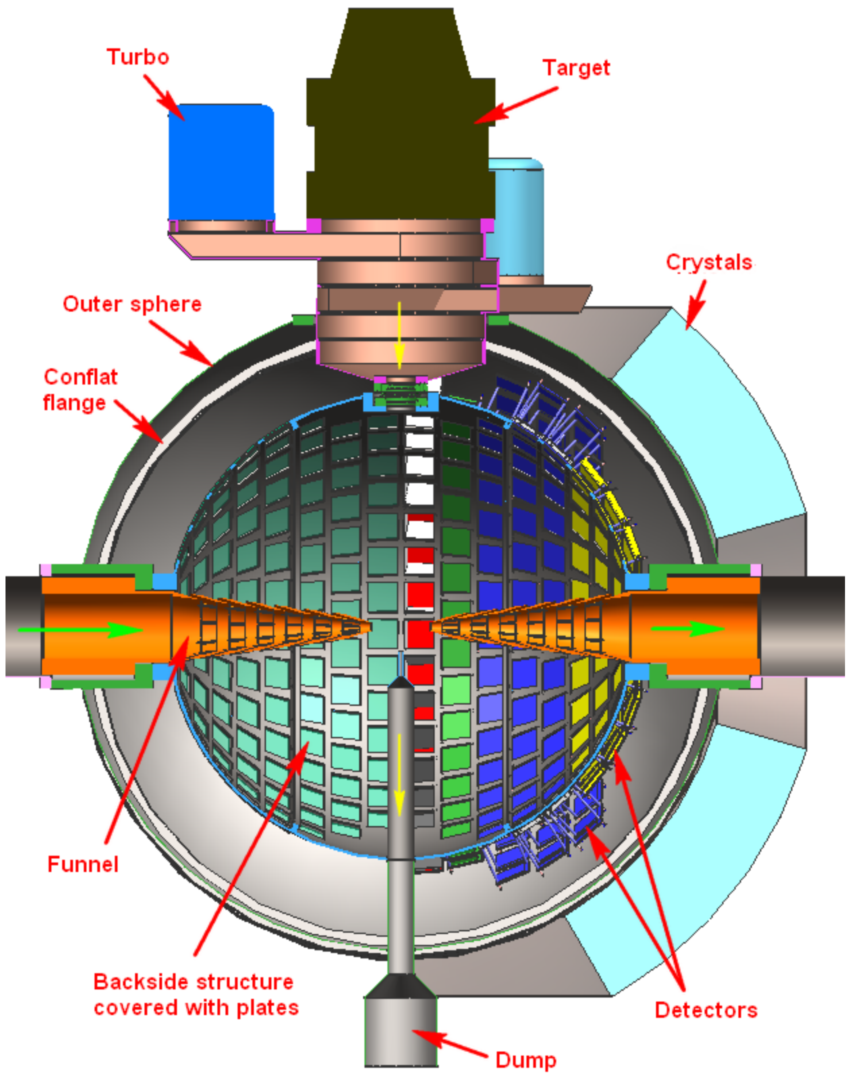




PSD

DSSD strip-strip events show PSD comparable with single PIN diodes

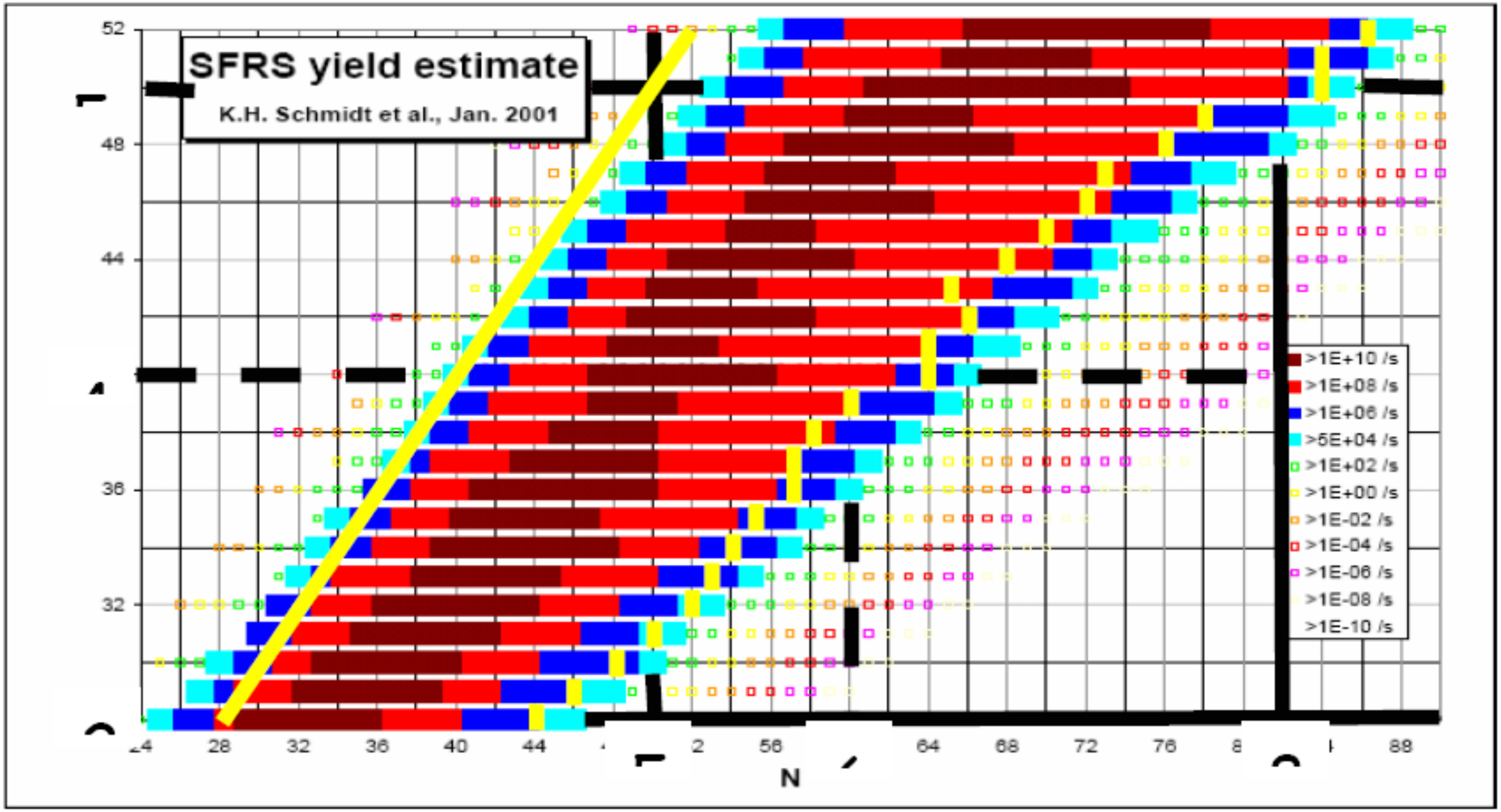
System Integration



Specifications of the Silicon Detectors for EXL

Angular region	Θ_{lab} [deg]	Detector type	Active area [mm²]	Thickness [mm]	Distance from target [cm]	Pitch [mm]	Number of detectors	Number of channels
A	89 - 80	DSSD Si(Li)	87 x 87 87 x 87	0.3 9	59 60	0.1 -	20 20	34800 180
B	80 - 75	DSSD Si(Li) Si(Li) Si(Li)	50 x 87 50 x 87 50 x 87 50 x 87	0.3 9 9 9	50 52 54 56	0.1 - - -	20 20 20 20	27400 180 180 180
C	75 - 45	DSSD DSSD	87 x 87 87 x 87	0.1 0.3	50 60	0.1 0.1	60 60	104400 34800
D	45 - 10	DSSD DSSD Si(Li)	87 x 87 87 x 87 87 x 87	0.1 0.3 9	49 59 60	0.1 0.1	60 80 80	104400 139200 720
E	170 - 120	DSSD Si(Li)	50 x 50 50 x 50	0.3 5	25 26	0.5 -	60 60	6000 240
E’	120 - 91	DSSD Si(Li)	87 x 87 87 x 87	0.3 5	59 60	0.1 -	60 60	104400 540
Total		DSSD Si(Li)					420 280	555400 2220

RIB production Rates at FAIR



Proposal E105:
Start up of part of the EXL physics program with ^{56}Ni

Spokespersons: N. Kalantar (KVI), P. Egelhof (GSI)
GSI contact: H. Weick (GSI)

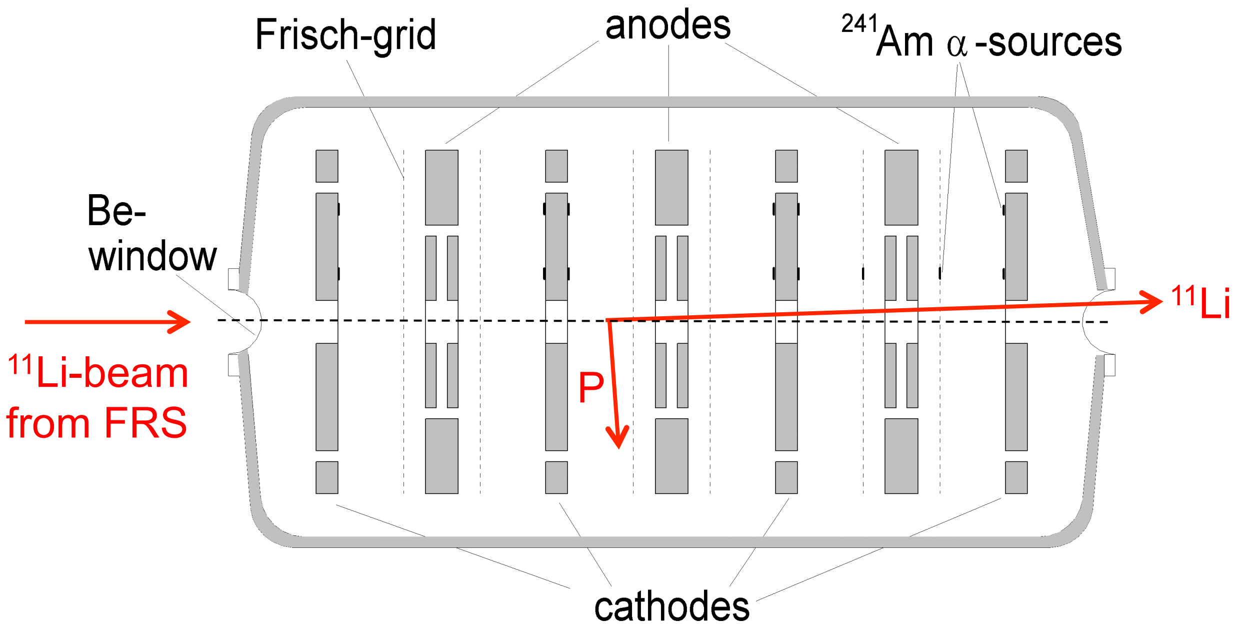
for the EXL collaboration

III.1. Experimental Concept: The TPC-Ionization Chamber IKAR as Active Target

(provided by PNPI St. Petersburg)

detection principle:

H_2-target = detector for recoil protons (from elastic scattering)

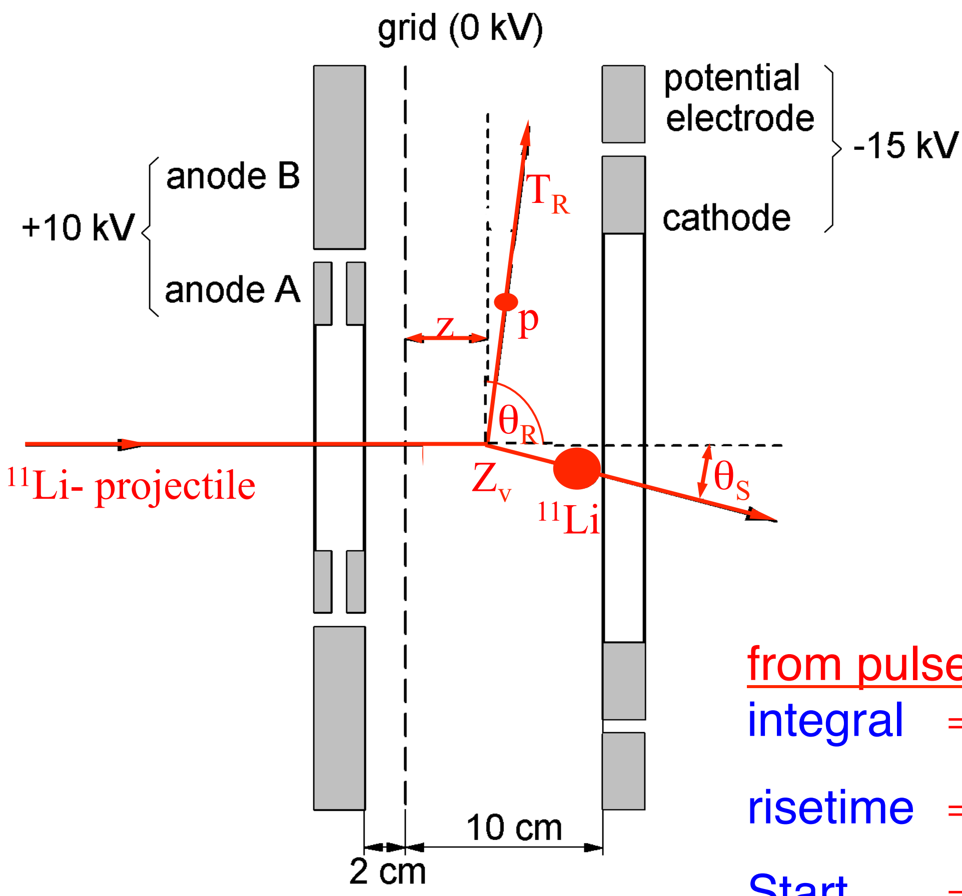


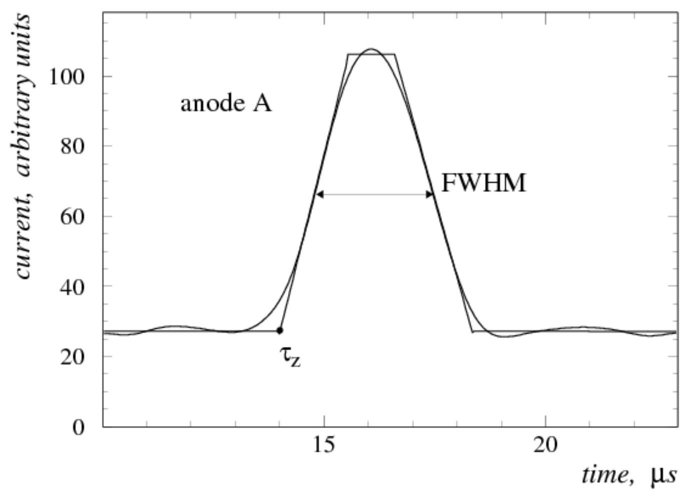
operating conditions:

H_2-pressure:	10 atm
entrance window:	0.5 mm Berylium
target thickness:	30 mg/cm² (6 independent sections)
beam rate:	$\leq 10^4$/sec

but: method limited to $Z \leq 6$!

Detection Principle of IKAR





<u>from pulse analysis:</u>

integral ⇒ recoil energy T_R ($\Delta E_{FWHM} \leq 90$ KeV)

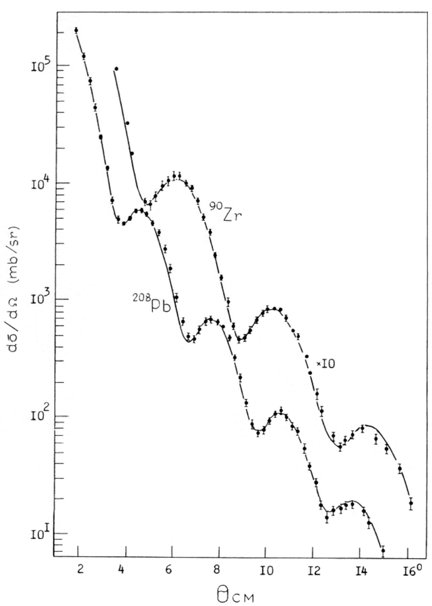
risetime ⇒ recoil angle θ_R ($\Delta\theta_{FWHM} \leq 0.6°$)

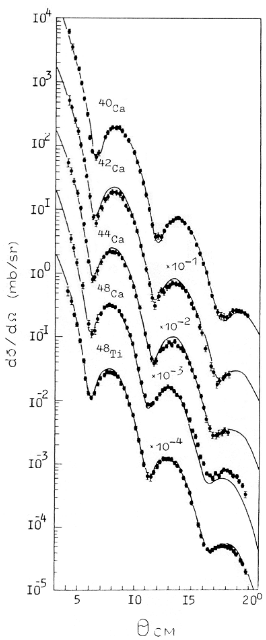
Start ⇒ vertex point Z_V ($\Delta z_{FWHM} \leq 110\ \mu$m)

Elastic Proton Scattering at Intermediate Energies around 1 GeV/u

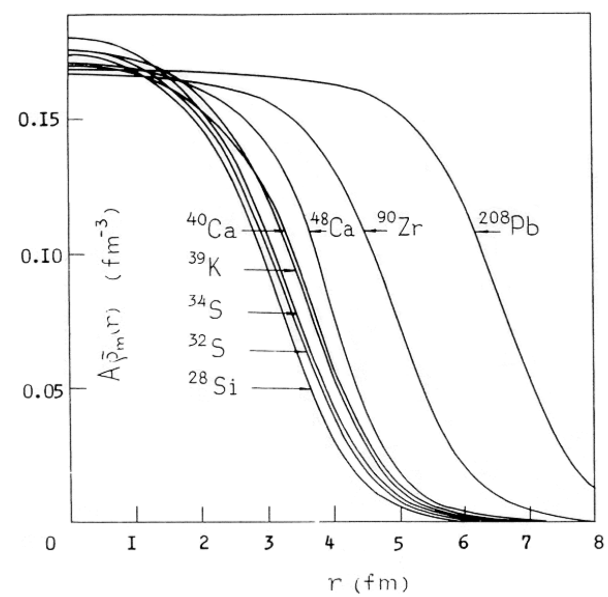
well established method to investigate nuclear matter distributions of stable nuclei (see G. Alkhazov et al., Phys. Rep. 42 (1978) 89)

measured cross sections





deduced nuclear matter distributions

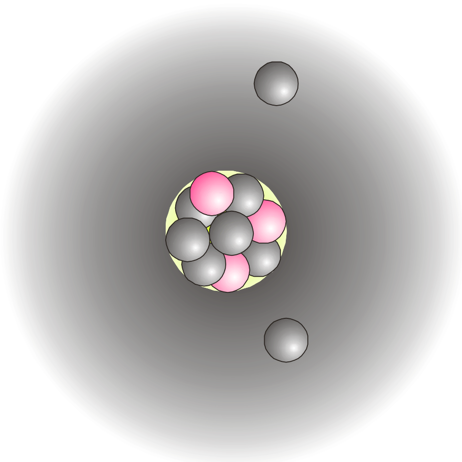


with radioactive beams ⇒ application to exotic nuclei

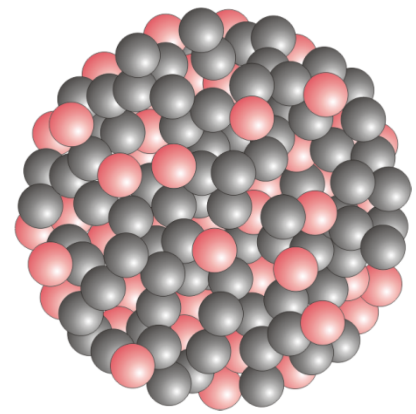
Halo-Nuclei – a New Phenomenon of the Structure of Nuclei

Density Distribution of Nuclear Matter

^{11}Li



^{208}Pb



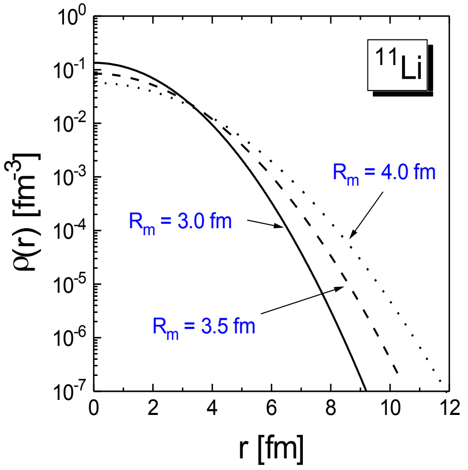
extremely neutron-rich nuclei:

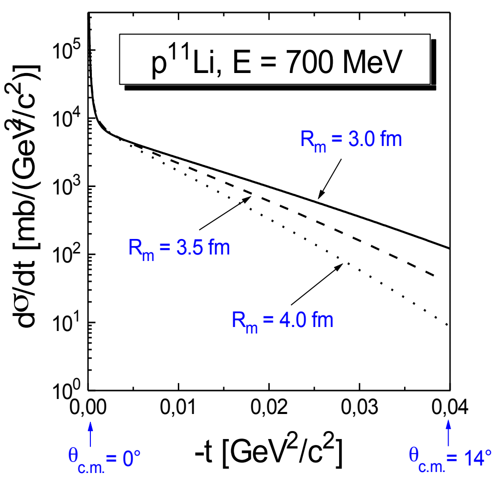
neutron halo

stable nuclei:

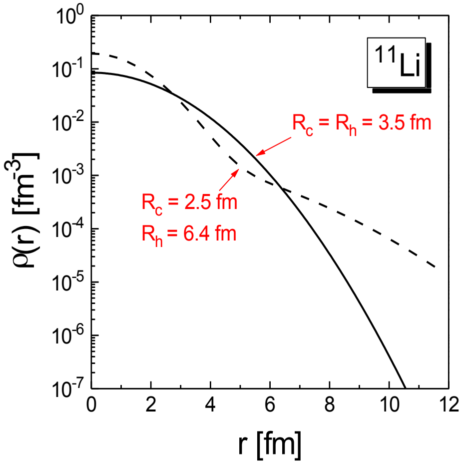
neutrons and protons equally distributed

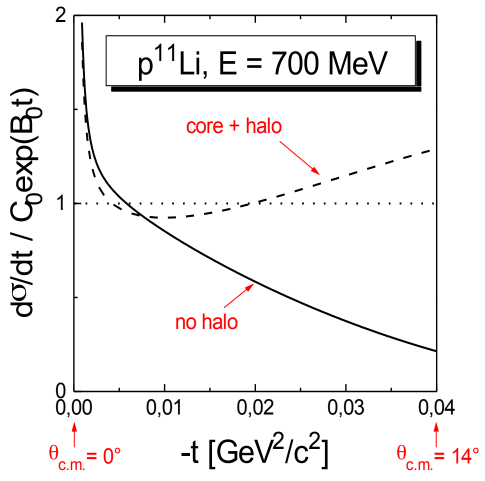
Sensitivity of Elastic Proton Scattering on the Radial Shape of the Nuclear Matter Distribution





slope of $d\sigma/dt$
→ matter radius R_m





curvature of log $(d\sigma/dt)$
→ halo structure

Determination of Neutron Radii and Neutron Skin Sizes

- needs input on proton (charge) distributions

  ⇒ use data from laser spectroscopy (isotope shift measurements):

  for ^{6}He: L.-B. Wang et al., PRL 93, 142501 (2004)

  for ^{8,9,11}Li: R. Sanchez et al., PRL 96, 033002 (2006)

  M. Puchalski et al., PRL 97, 1330016 (2006)

- neutron radius:

$$R_n^{\,2} = \frac{1}{N_n} * \left(A R_m^{\,2} - N_p R_p^{\,2} \right)$$

- neutron skin size:

$$\delta_{np} = R_n - R_p$$

Summary of all Data on Nuclear Radii

nucleus	R_m, fm	R_{core}, fm	R_{halo}, fm	R_p*, fm	R_n, fm	δ_{np}, fm
^{6}He	2.45 (10)	1.88 (12)	3.31 (28)	1.91 (2)	2.60 (7)	0.69 (7)
^{8}Li	2.50 (6)	--	--	2.15 (3)	2.69 (9)	0.54 (10)
^{9}Li	2.44 (6)	--	--	2.06 (4)	2.61 (9)	0.55 (10)
^{11}Li	3.71 (20)	2.53 (3)	6.85 (58)	2.33(4)	3.75 (15)	1.42 (16)

* R_p from laser spectroscopy, unfolded from proton charge radius

Application of an Active Target for (α,α`γ)
(proposed by D. Savran)

PDR in inelastic α scattering experiments

Problems in (α,α'):

- Separation from other excitations, no selectivity to E1 in the excitation

Signature: Strong decay to the ground state

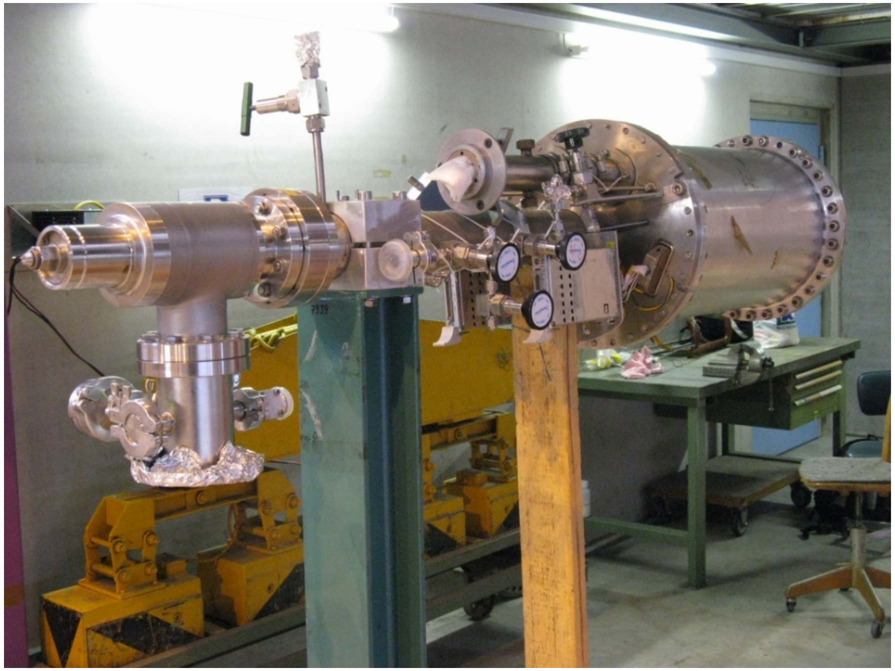
Coincident γ-decay detection:

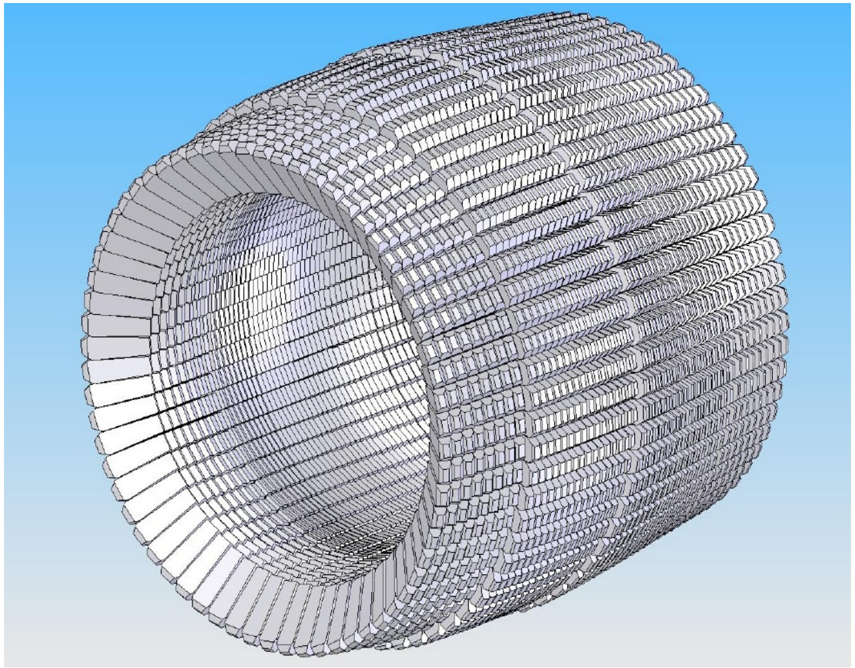
- Selection of decays to the ground state

⇒ Selectivity to E1

T.D. Poelhekken et al., Phys. Lett. B **278** (1992) 423
D. Savran et al., Nucl. Instr. and Meth. A **564** (2006) 267

Application of an Active Target for (α,α`γ)
(proposed by D. Savran)





Existing chamber at PSI

CALIFA γ-detector

Geometrically fits into CALIFA

recent test run successful