The Radial Shape of Exotic Nuclei from Intermediate Energy Elastic Proton Scattering

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Neutron Skins of Nuclei

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– a Tool to Study the Radial Shape of Exotic Nuclei

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IV. Results for Light Nuclei at Higher q

V. Results for Heavier Nuclei from Storage Ring Experiments

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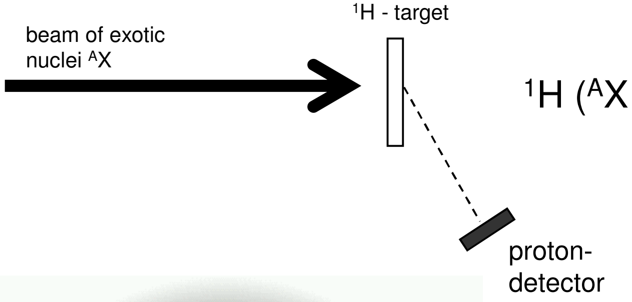
I. Introduction

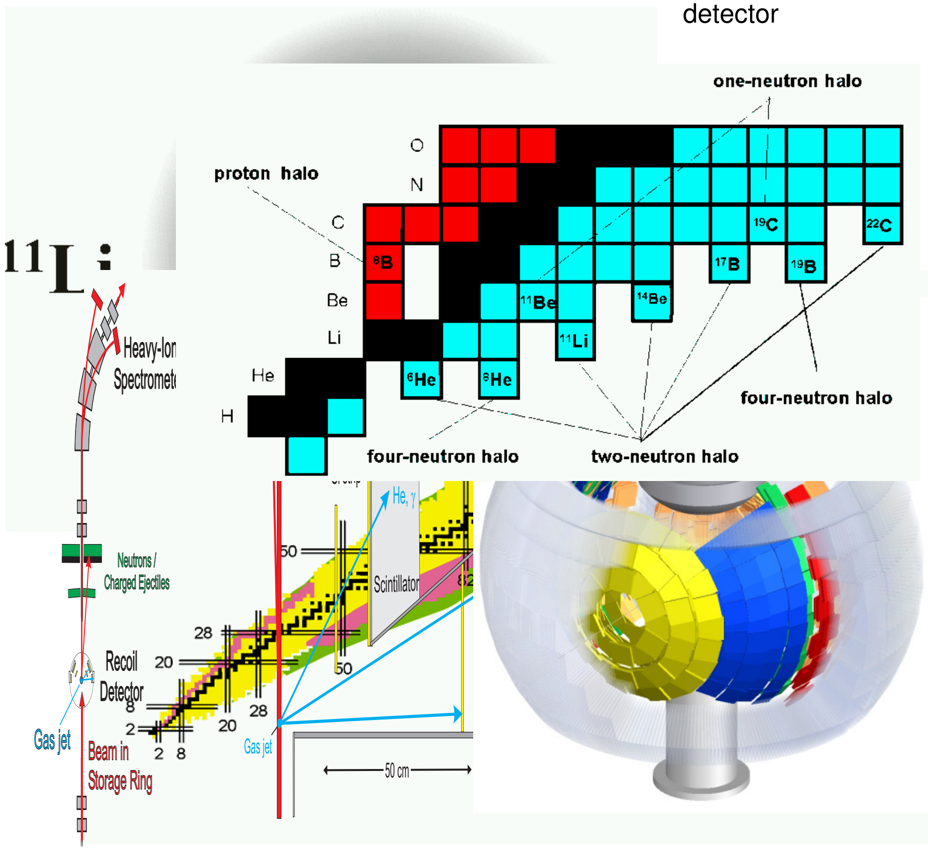


classical method of nuclear spectroscopy:

⇒ light ion induced direct reactions: (p,p), (p,p'), (d,p), ...
⇒ to investigate exotic nuclei: inverse kinematics

past and present experiments:

⇒ light neutron-rich nuclei: skin, halo structures
⇒ new technology: concept of active target



future perspectives at FAIR:

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

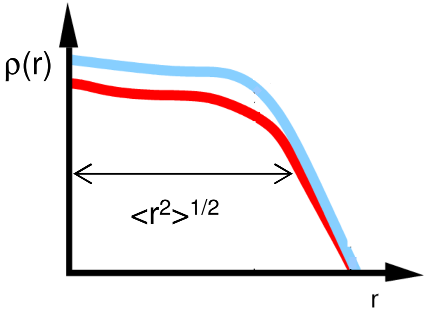
EXL: direct reactions at internal NESR target

⇒ high luminosity even for very low momentum transfer measurements

I. Introduction

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

$\Rightarrow$ of high interest for nuclear structure and astrophysics



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

standard methods: (see also C.J. Batty et al., Adv. in Nucl. Phys. 19 (1989) 1-188)

nuclear charge distribution: electron scattering
isotope shifts
muonic atoms

nuclear matter distribution: (p,p), (α,α), (π,π), ...

Definitions

- all nucleon distributions given are <u>point distributions</u> (distributions of point nucleons)

- nuclear matter distribution $\rho_m(r)$ $\Rightarrow$ nuclear matter radius $R_m = \langle r_m^2 \rangle^{1/2}$

  proton (charge) distribution $\rho_p(r)$ $\Rightarrow$ proton (charge) radius $R_p = \langle r_p^2 \rangle^{1/2}$

  neutron distribution $\rho_n(r)$ $\Rightarrow$ neutron radius $R_n = \langle r_n^2 \rangle^{1/2}$

- $\rho_m(r) = \rho_p(r) + \rho_n(r)$, where ρ_p, ρ_n are normalized to number of protons, neutrons

  $\Rightarrow A\, R_m^2 = N_p R_p^2 + N_n R_n^2$

- neutron skin thickness: $\delta_{np} = R_n - R_p$

- note that experimentally determined charge densities are folded with size of the proton!

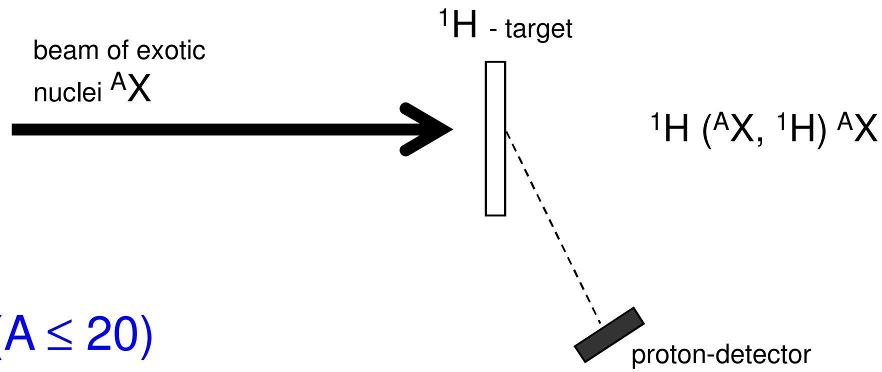
Direct Reactions in Inverse Kinematics

classical method to observe spectroscopic information:

⇒ light ion induced direct reactions: (p,p), (p,p'), (d,p), …
(before RIB-facilities: limited to stable nuclei)

aim: use radioactive beams from RIB-facilities for nuclear structure studies off stability

method: Inverse Kinematics



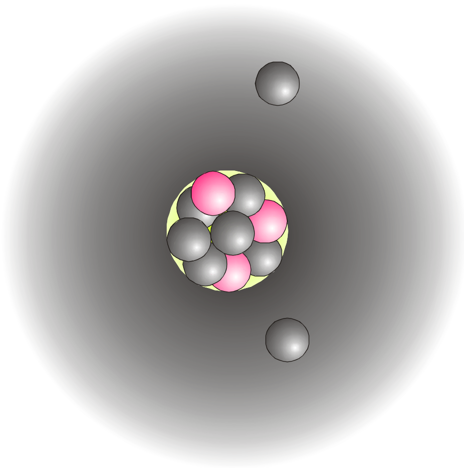
first generation experiments:

- mainly light neutron-rich nuclei ($A \leq 20$)
- extreme N/Z ratio
  ⇒ new phenomena of nuclear structure

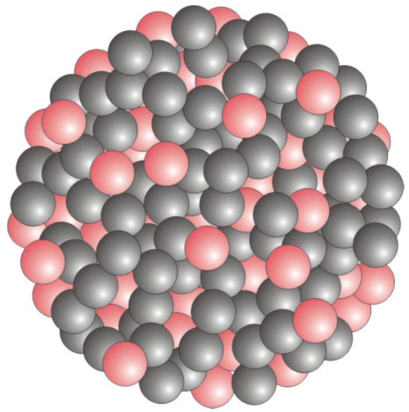
Halo-Nuclei – a New Phenomenon of the Structure of Nuclei

Density Distribution of Nuclear Matter

^{11}Li



^{208}Pb



extremely neutron-rich nuclei:

neutron halo

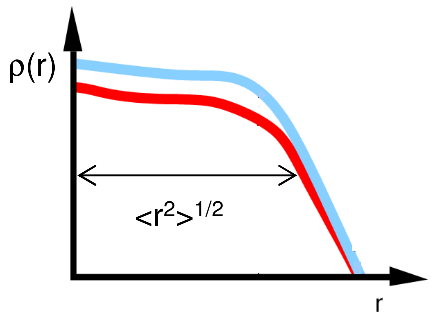
stable nuclei:

neutrons and protons equally distributed

II. Intermediate Energy 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 and astrophysics



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

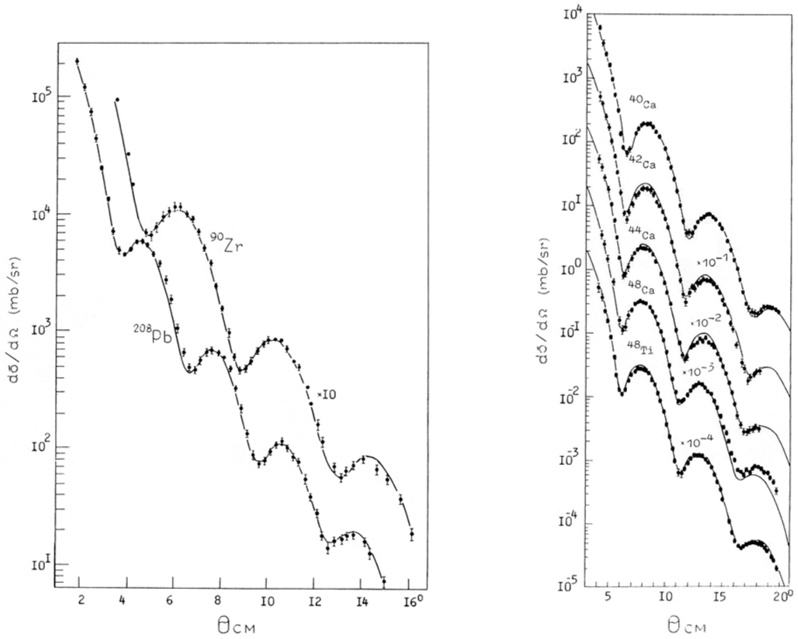
⇒ well established method for determination of nuclear matter distributions (of stable nuclei)

⇒ what about exotic nuclei?

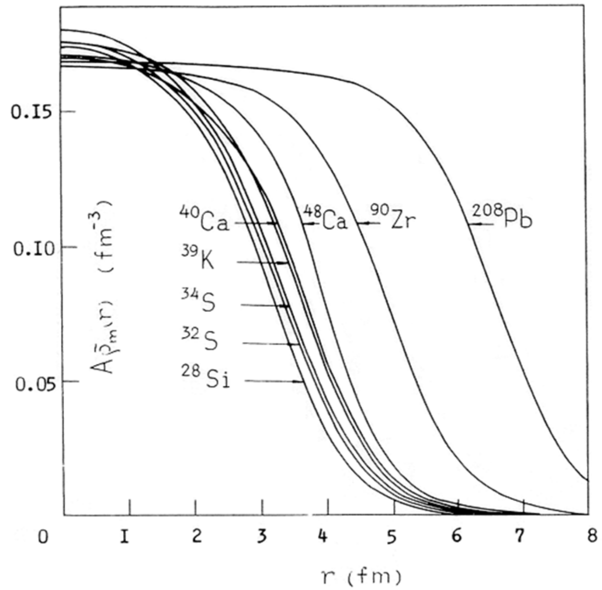
Elastic Proton Scattering at Intermediate Energies around 1 GeV/u

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

Proton Scattering from Stable Nuclei

PHYSICAL REVIEW C **82**, 044611 (2010)

Neutron density distributions of ^{204,206,208}Pb deduced via proton elastic scattering at $E_p = 295$ MeV

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(Received 12 September 2010; published 22 October 2010)

Cross sections and analyzing powers for polarized proton elastic scattering from ^{58}Ni, and ^{204,206,208}Pb were measured at intermediate energy $E_p = 295$ MeV. An effective relativistic Love-Franey interaction is tuned to reproduce ^{58}Ni scattering data within the framework of the relativistic impulse approximation. The neutron densities of the lead isotopes are deduced using model-independent sum-of-Gaussians distributions. Their error envelopes are estimated by a new χ^2 criterion including uncertainties associated with the reaction model. The systematic behaviors of extracted error envelopes of the neutron density distributions in ^{204,206,208}Pb are presented. The extracted neutron and proton density distribution of ^{208}Pb gives a neutron skin thickness of $\Delta r_{np} = 0.211^{+0.054}_{-0.063}$ fm.

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:

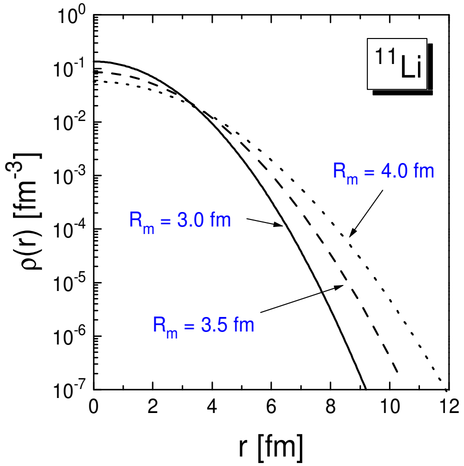
high sensitivity on the halo structure

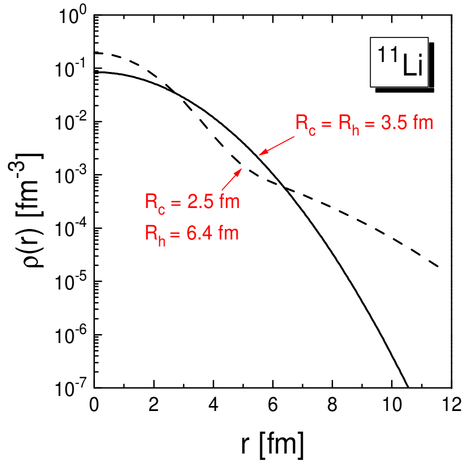
$\Rightarrow$ determination of matter radii

$\Rightarrow$ determination of the radial shape of the nuclear matter distribution

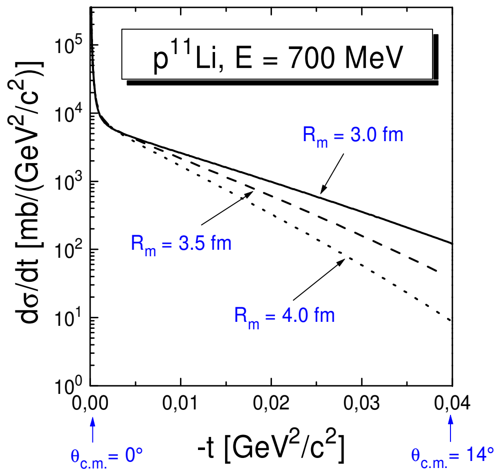
Sensitivity of Elastic Proton Scattering on the Radial Shape of the Nuclear Matter Distribution

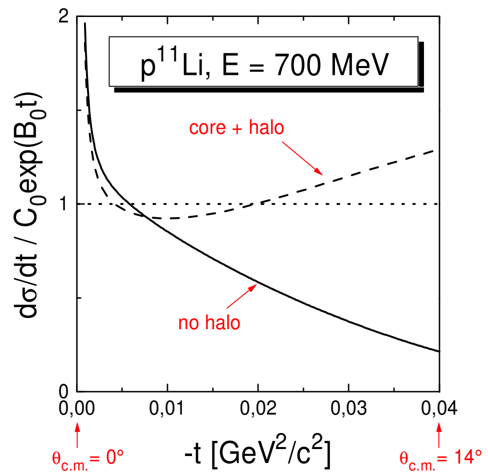
assumed matter distribution:





dσ/dt for p-scattering at E=700 MeV:





slope of dσ/dt
→ matter radius R_m

curvature of log (dσ/dt)
→ halo structure

Elastic Proton Scattering at Low and Intermediate Energies

for intermediate energy proton scattering ($E_p \geq 700 - 1000$ MeV):

reaction mechanism and effective nucleon-nucleon interaction well defined

$\Rightarrow$ Matter distribution $\rho(r)$ related to differential cross sections in straight forward way (Glauber theory)

for low energy proton scattering ($E_p = 20 - 100$ MeV):

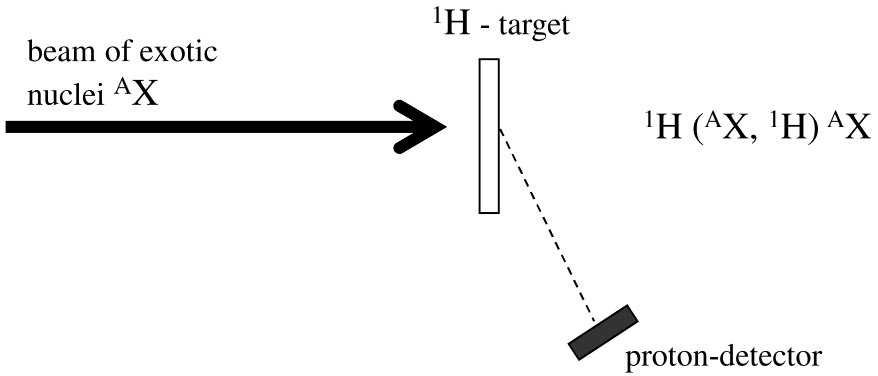
quantitative determination of $\rho(r)$ limited by:

- potential ambiguities
- uncertainties in effective pp, pn interaction

Experiments at Low Momentum Transfer

experimental conditions:

- investigation of exotic nuclei
  ⇒ method of “Inverse Kinematics”



- high incident energies (E = 700 MeV/u)
  ⇒ produce beam of exotic nuclei by projectile fragmentation at GSI: Fragment Separator FRS
- low beam intensities: $10^2 – 10^4$ sec^{-1}
- low recoil energies: $T_R \leq 10$ MeV
  ⇒ needs thin target and large solid angle detector
  solution: recoil detector “IKAR” as active target

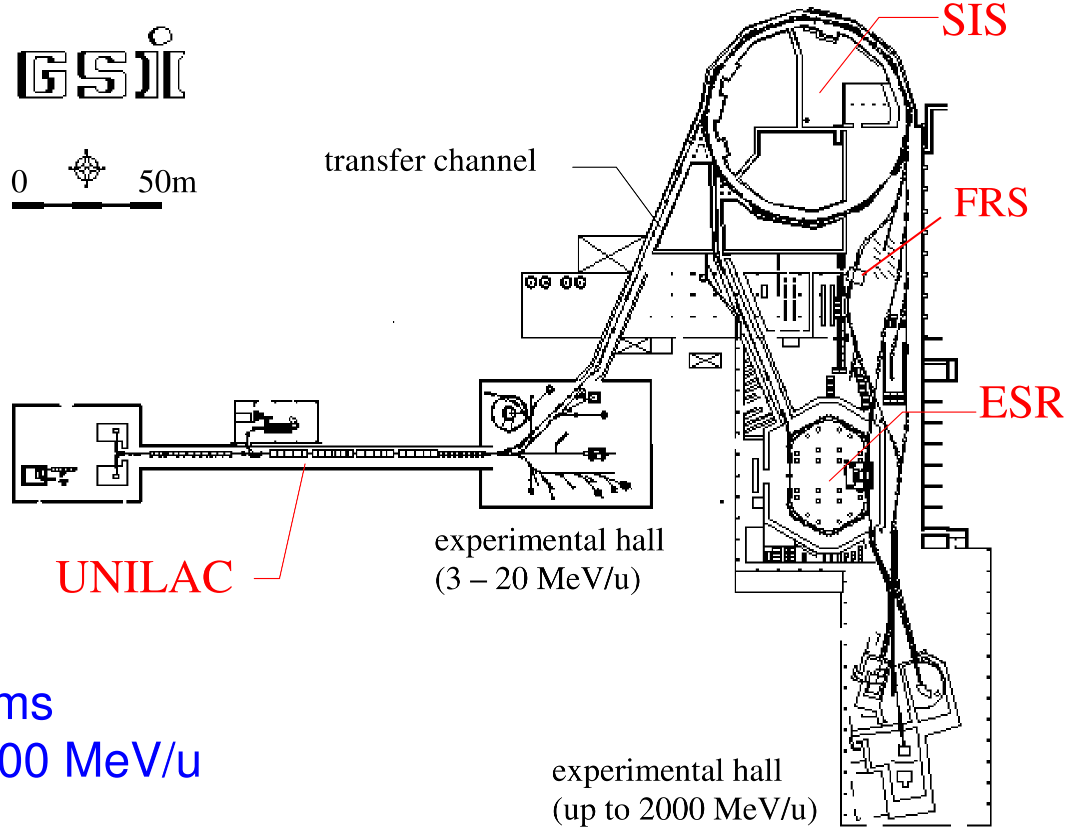
The Present GSI Accelerator Facilities

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

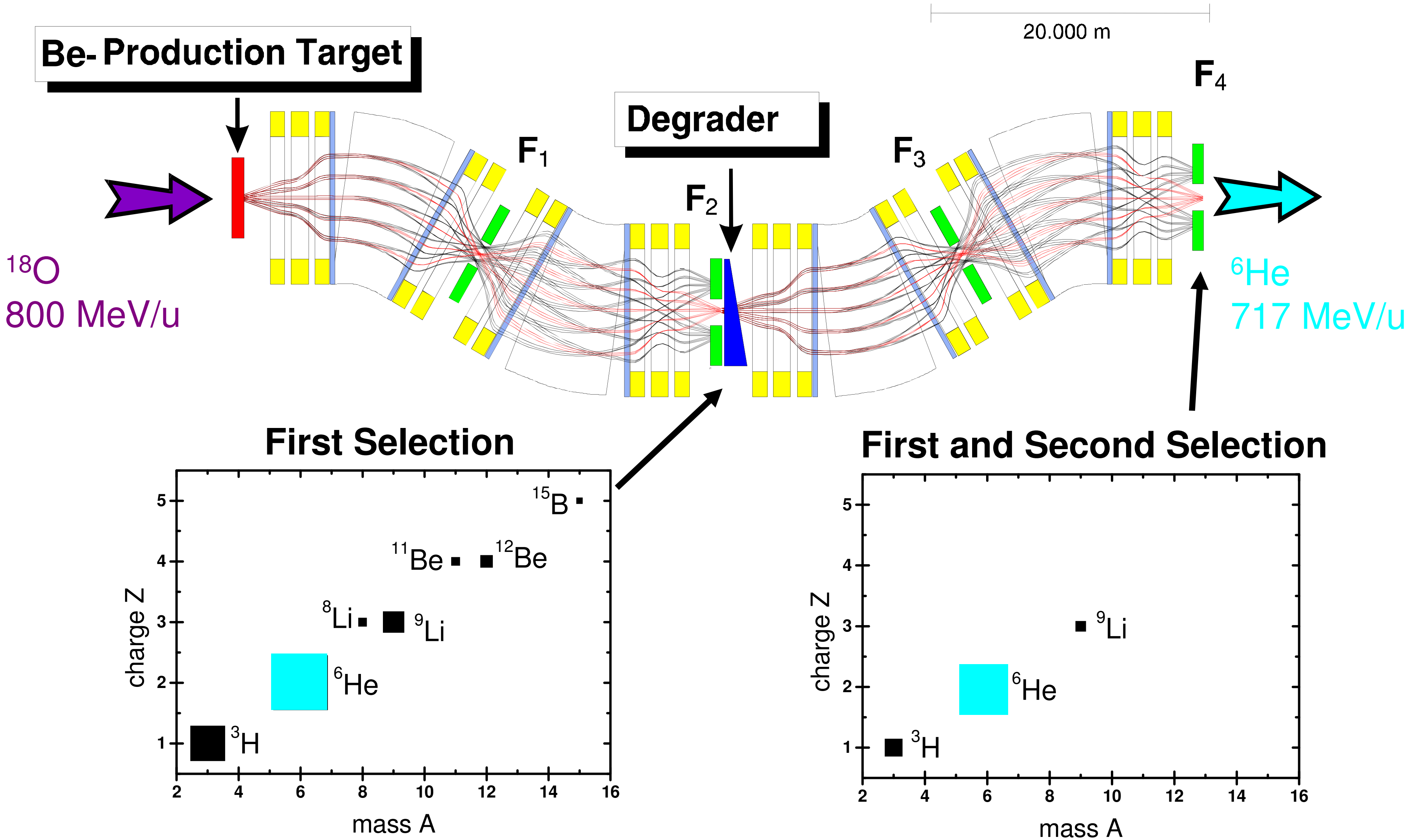
SIS: heavy ion synchrotron
E = 100 - 2000 MeV/u

ESR: experimental storage ring
beam cooling
⇒ excellent beam qualities

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

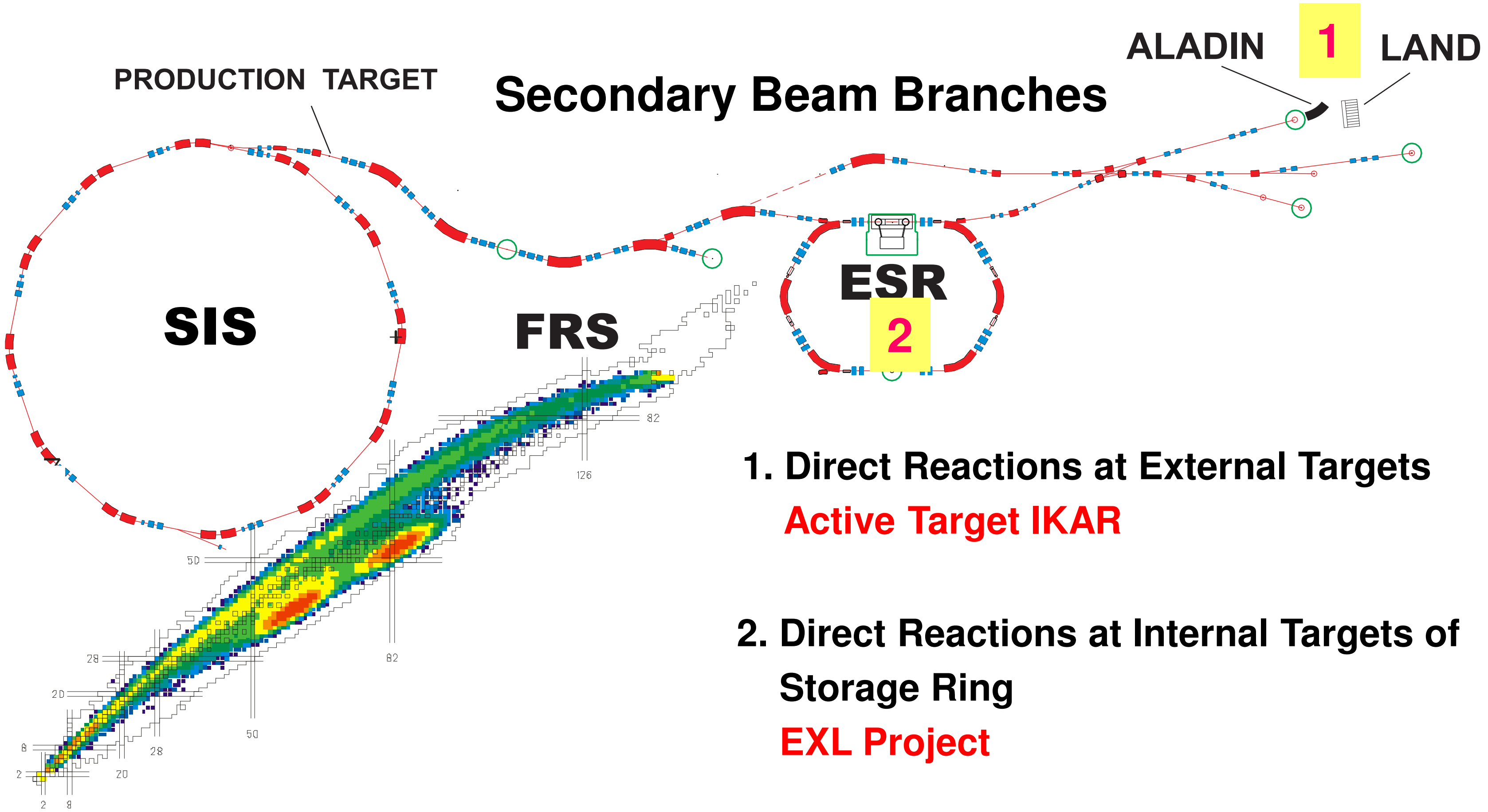


Production and Separation of Exotic Nuclei with the FRS



The Present Radioactive Beam Facility at GSI

FRS: In-Flight Separator & High-Resolution Spectrometer



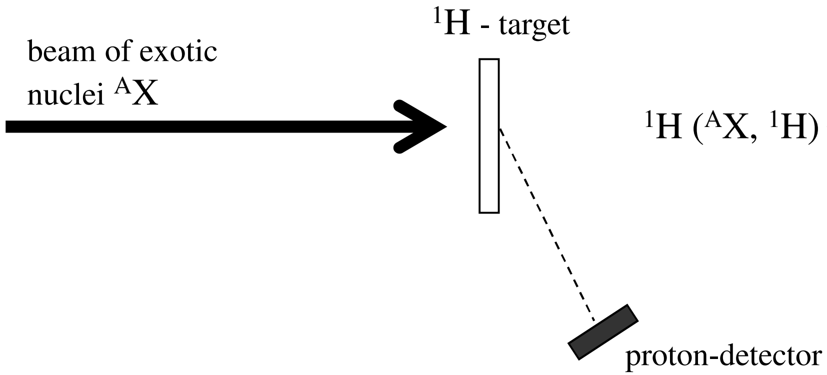
1. Direct Reactions at External Targets
   Active Target IKAR

2. Direct Reactions at Internal Targets of Storage Ring
   EXL Project

Experiments at Low Momentum Transfer

<u>experimental conditions:</u>

- investigation of exotic nuclei
  ⇒ method of "Inverse Kinematics"



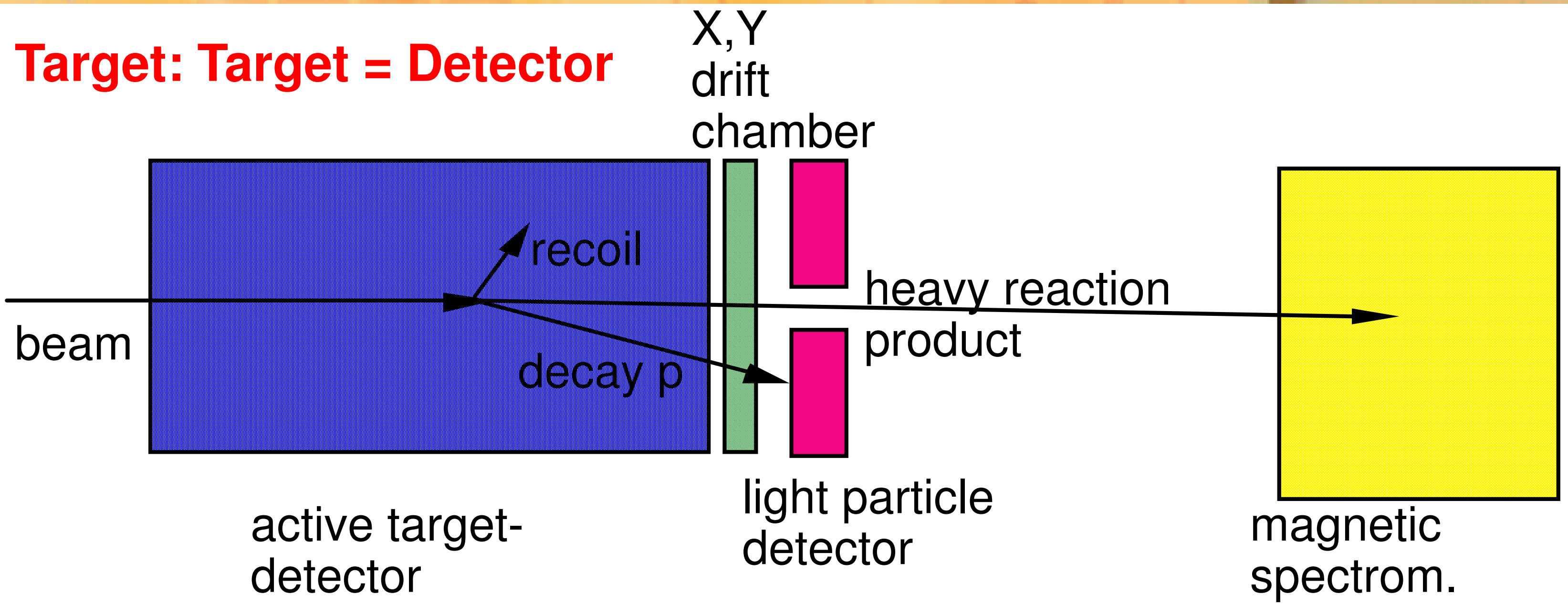
$^{1}H\,(^{A}X,\,^{1}H)\,^{A}X$

- high incident energies (E = 700 MeV/u)
  ⇒ produce beam of exotic nuclei by projectile fragmentation at GSI: Fragment Separator FRS

- low beam intensities: $10^{2} – 10^{4}\ sec^{-1}$
- low recoil energies: $T_R \leq 10$ MeV
  ⇒ needs thin target and large solid angle detector
  <u>solution:</u> recoil detector <u>"IKAR"</u> as <u>active target</u>

Direct Reactions with Active Targets

Active Target: Target = Detector



⇒ advantage:

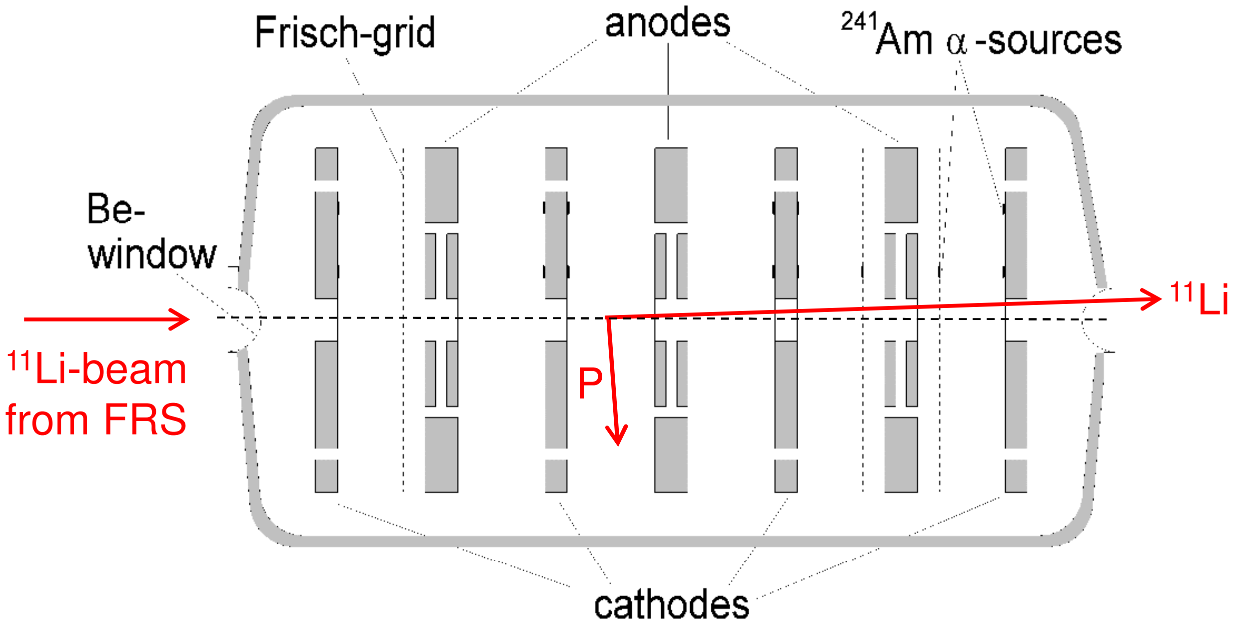
- low threshold
- high detection efficiency (rel. thick target)

The TPC-Ionization Chamber IKAR as Active Target

(provided by PNPI St. Petersburg)

<u>detection principle:</u>

H_2-target = detector for recoil protons

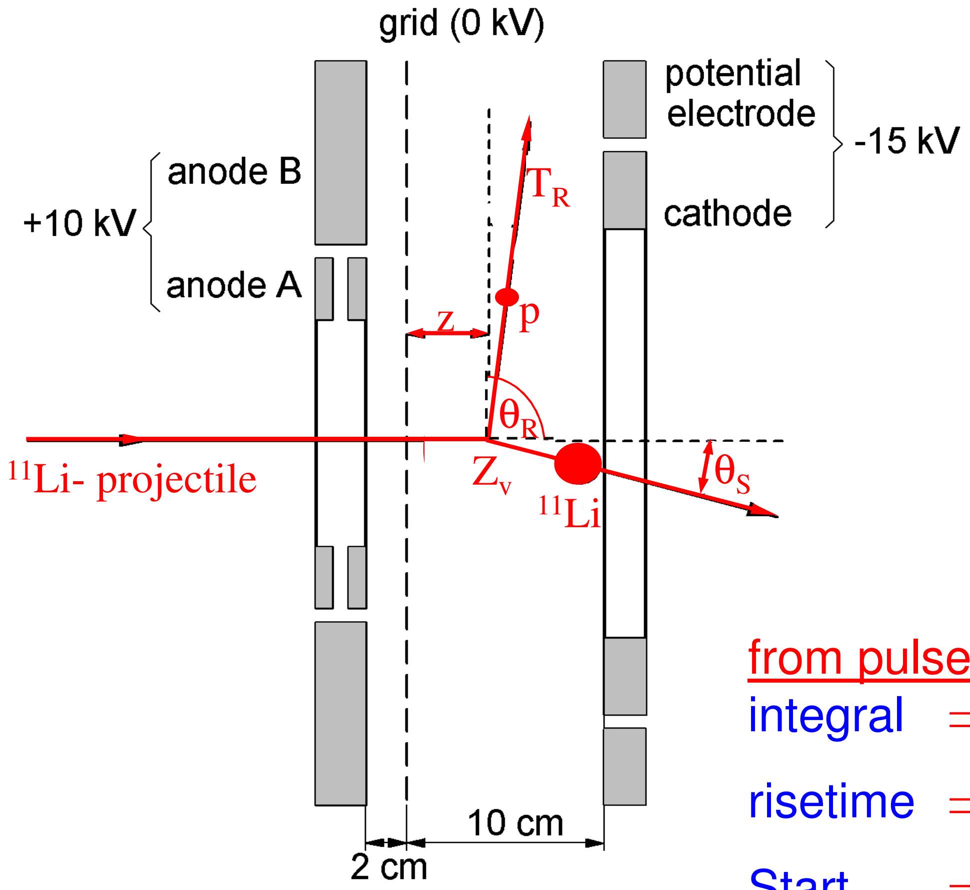


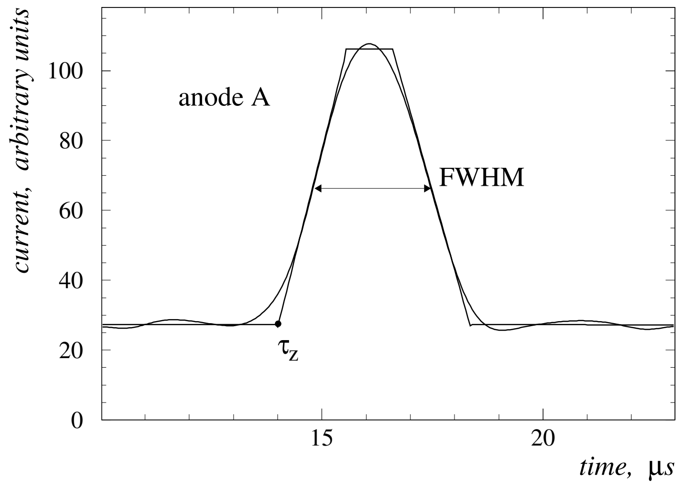
<u>operating conditions:</u>

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

<u>but</u>: method limited to Z ≤ 6!

Detection Principle of IKAR





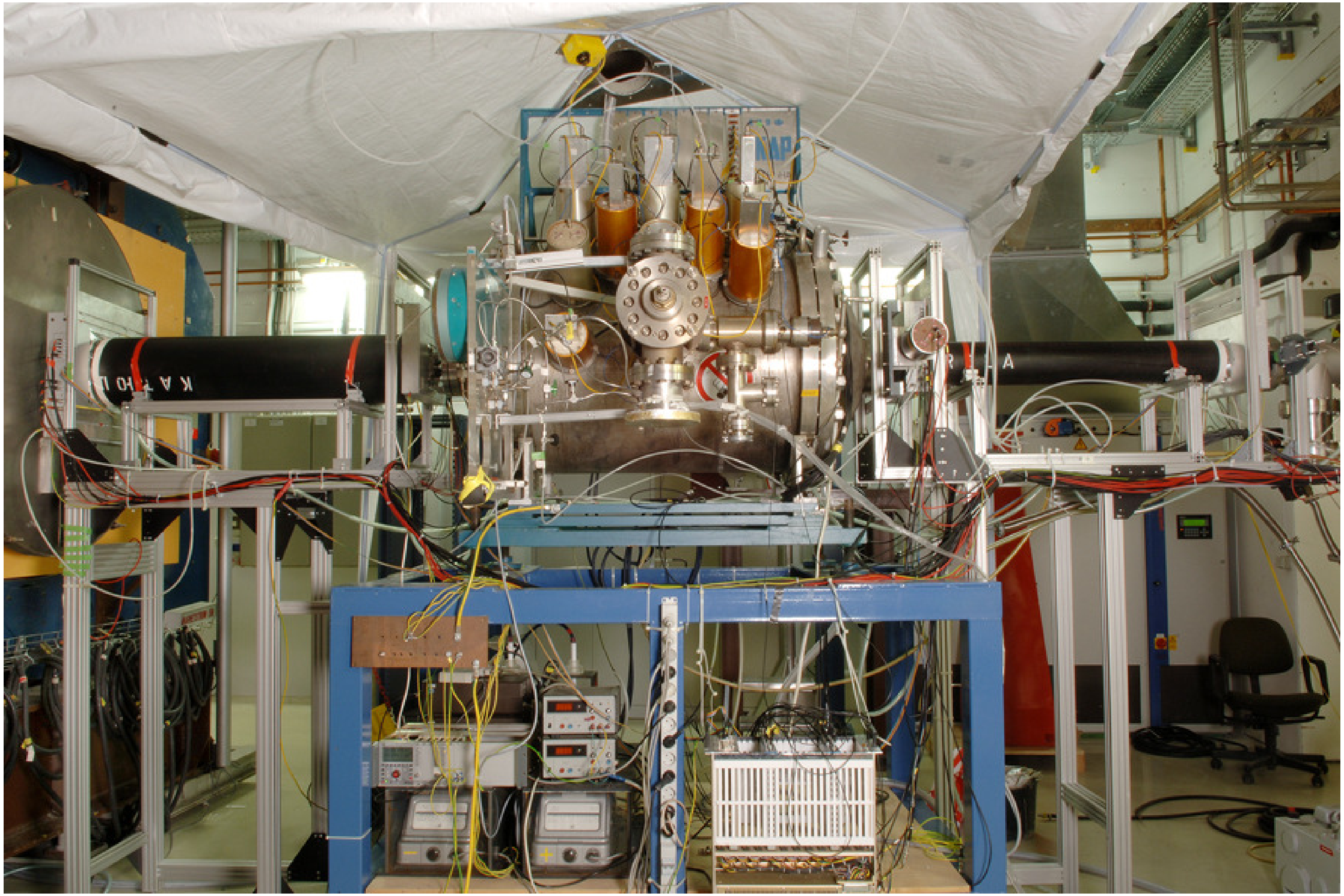
from pulse analysis:

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

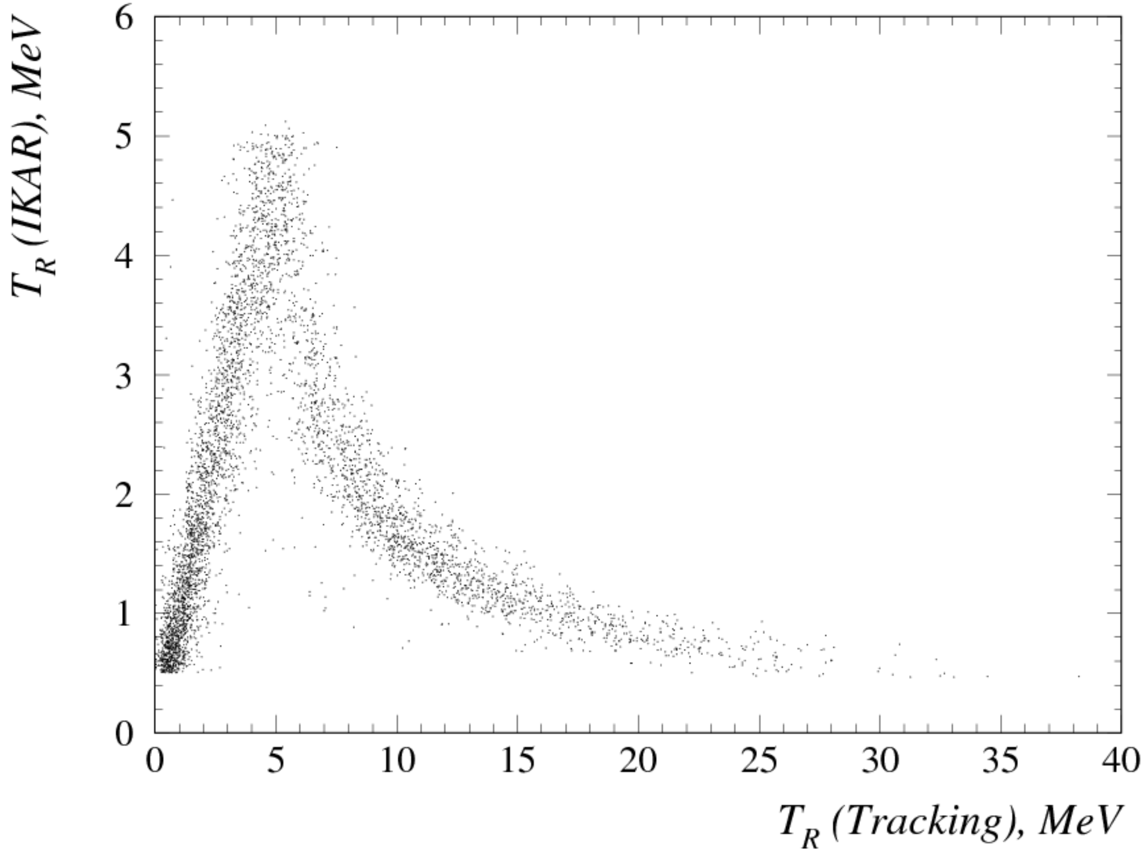
risetime ⇒ recoil angle θ_R ($\Delta\theta_{FWHM} \leq 0.6°$)

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

The IKAR Experimental Setup



Data Analysis



T_R (IKAR): recoil-energy measured in the IKAR-detector

T_R (Tracking): recoil-energy calculated from the measured scattering angle:
$T_R = \theta_S^2\, p^2/2m_p$

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

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)

Free pp and pn Scattering

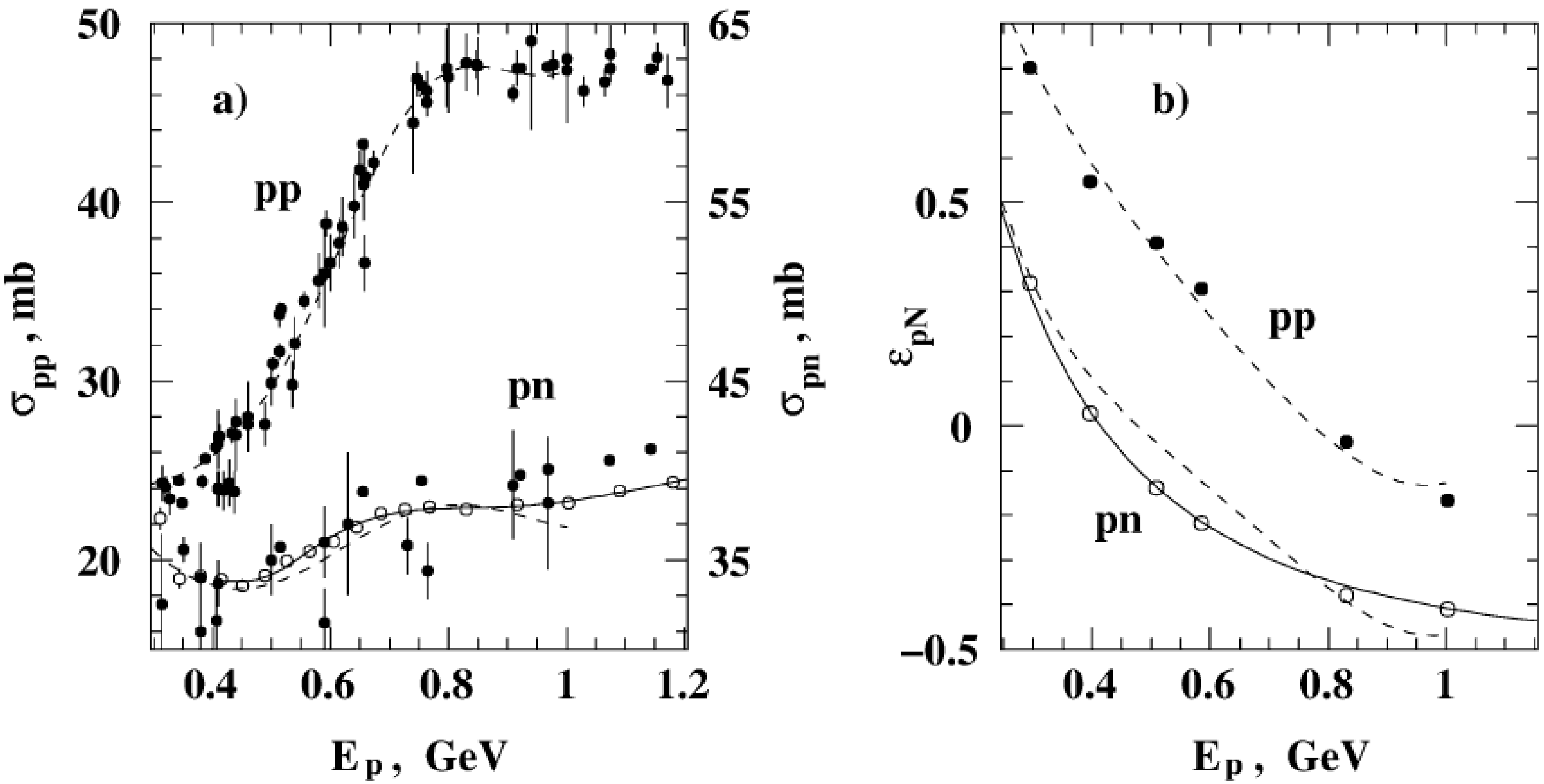
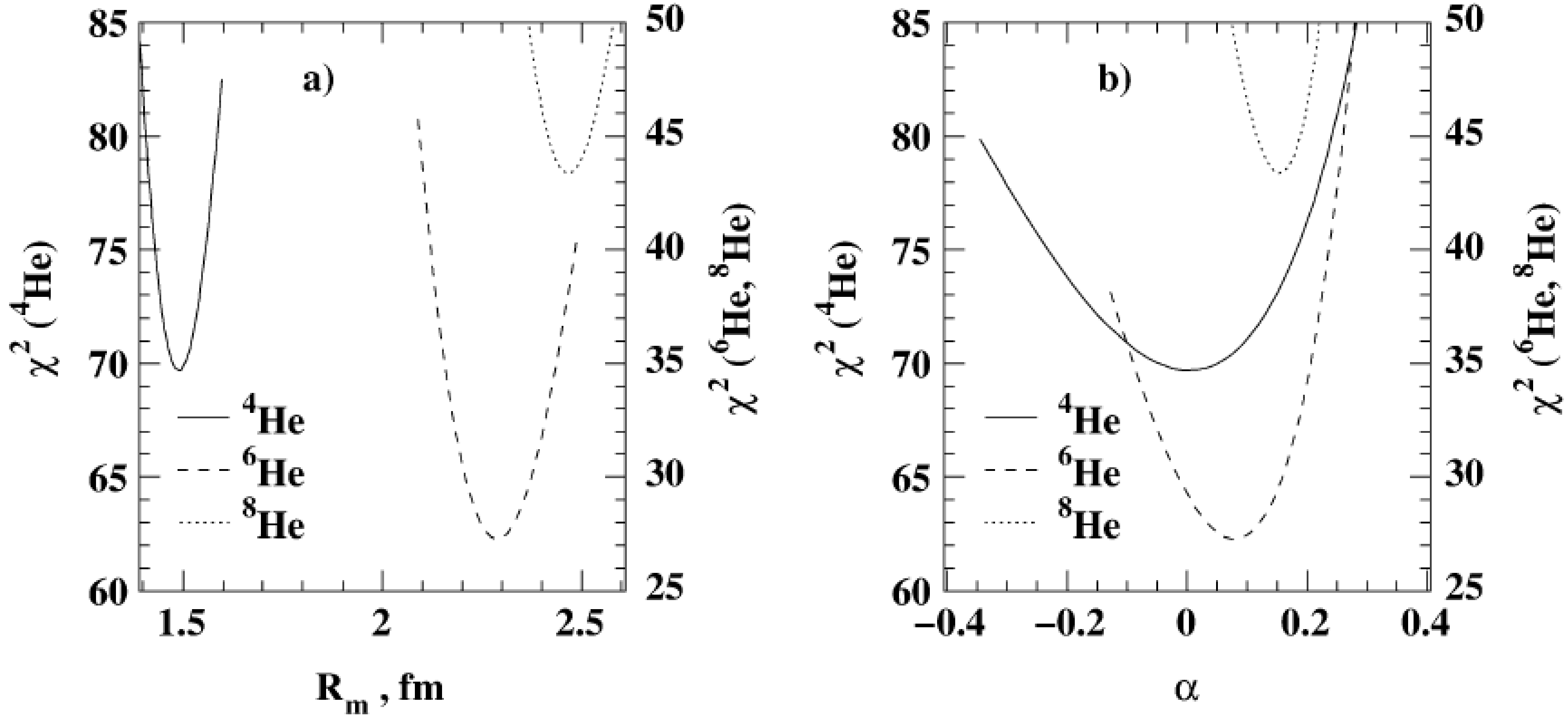


Fig. 2. (a) Energy dependence of the total cross sections σ_{pN} for free *pp* and *pn* scattering. The data are from Ref. [9] (dots and circles). The dashed curves result from a phase shift analysis [8]. The solid line is a smooth-function fit to the data from Ref. [10] (circles). (b) Energy dependence of the ratios ϵ_{pN} of the real to the imaginary part of the *pp* and *pn* scattering amplitudes (dots and circles, respectively) obtained with the help of dispersion relations [11]. The data for *pn* scattering are fitted by a smooth function (solid line). The dashed lines represent the results of a phase shift analysis [8].

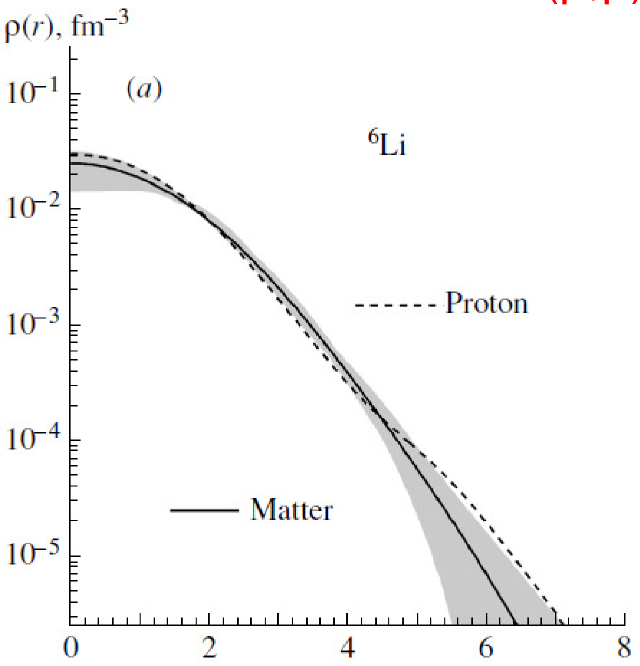
χ^2 Analysis



Comparison of Matter Distribution and Charge Distribution of ^{6}Li and ^{4}He

for ^{6}Li: charge distribution from (e,e) scattering (G.C. Li et al., Nucl. Phys. A 162 (1971) 583)

matter distribution from (p,p) scattering (present experiment)



charge radius: R_{ch} = 2.56 (5) fm

matter radius: R_m = 2.58 (7) fm
(folded with size of the nucleon)

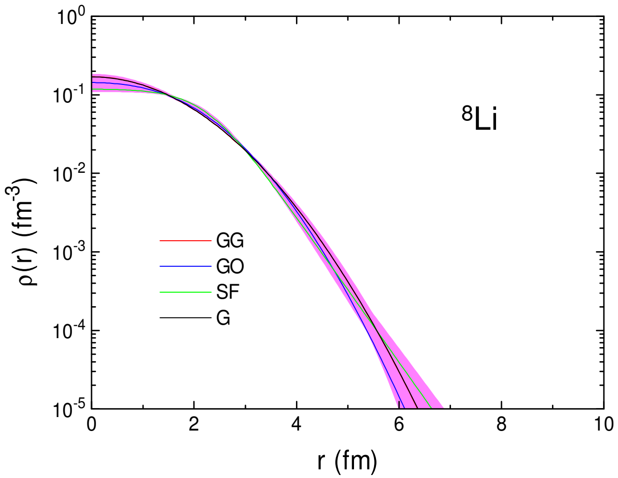
for ^{4}He: charge radius from (e,e) scattering: R_{ch}=1.46 (6)(I.Sick et al., PRC77(2008)041302

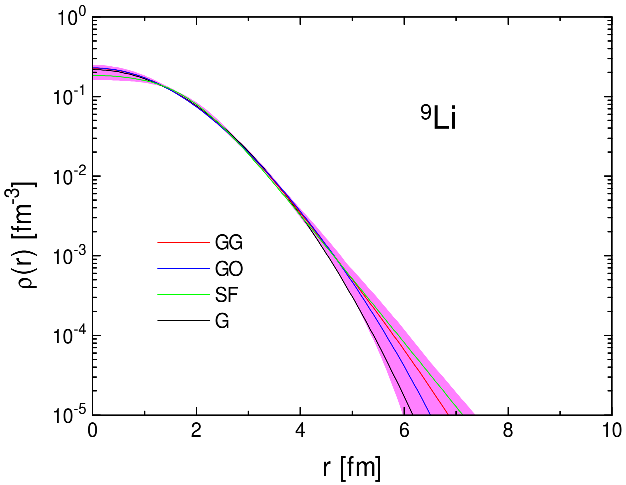
matter radius from (p,p) scattering: R_m=1.49(3)

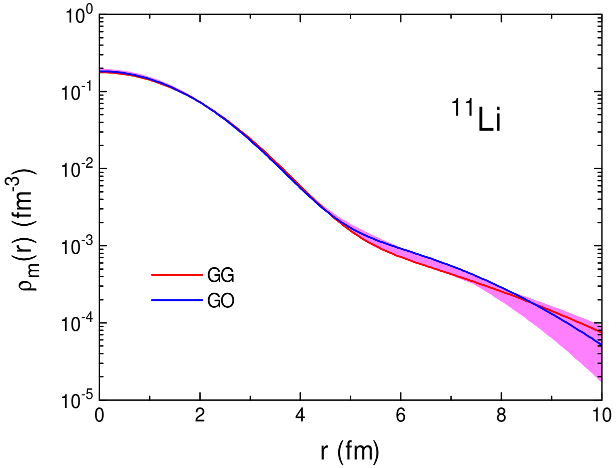
good agreement

⇒ confirmation of experimental method and concept of data analysis

III. Results on the Li Isotopes





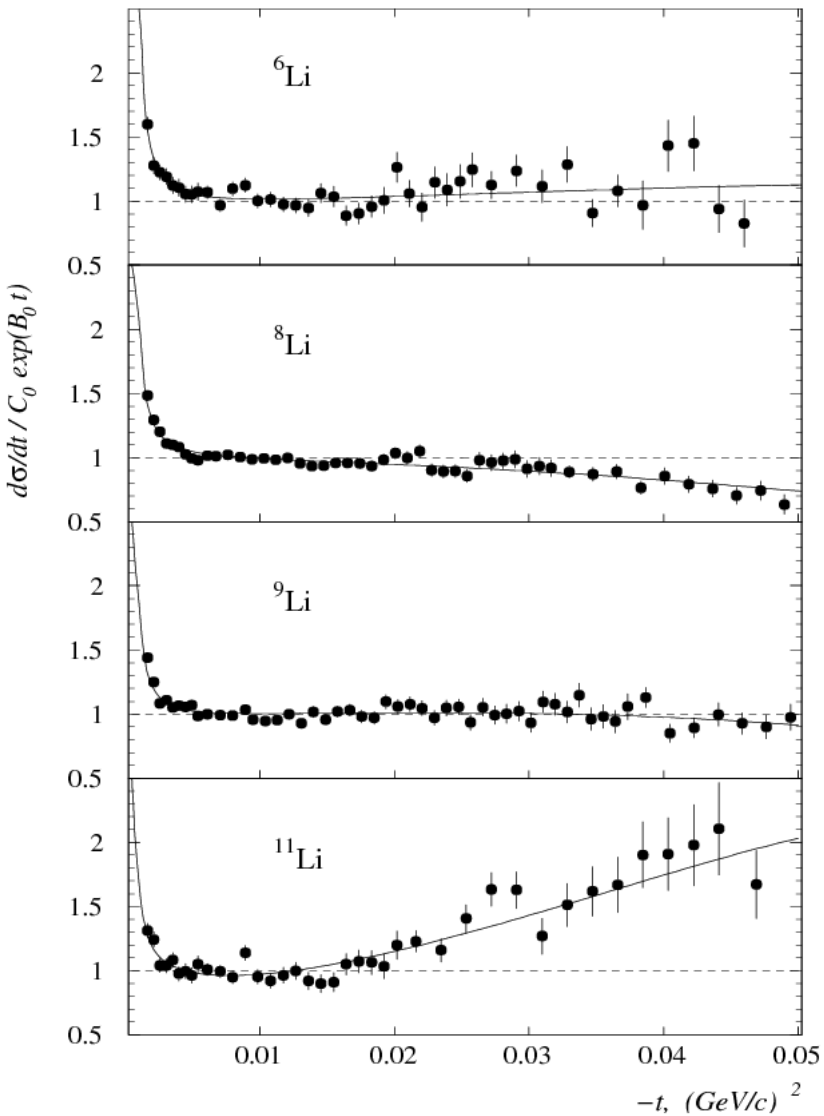


R_m = 2.50 (6) fm

R_m = 2.44 (6) fm

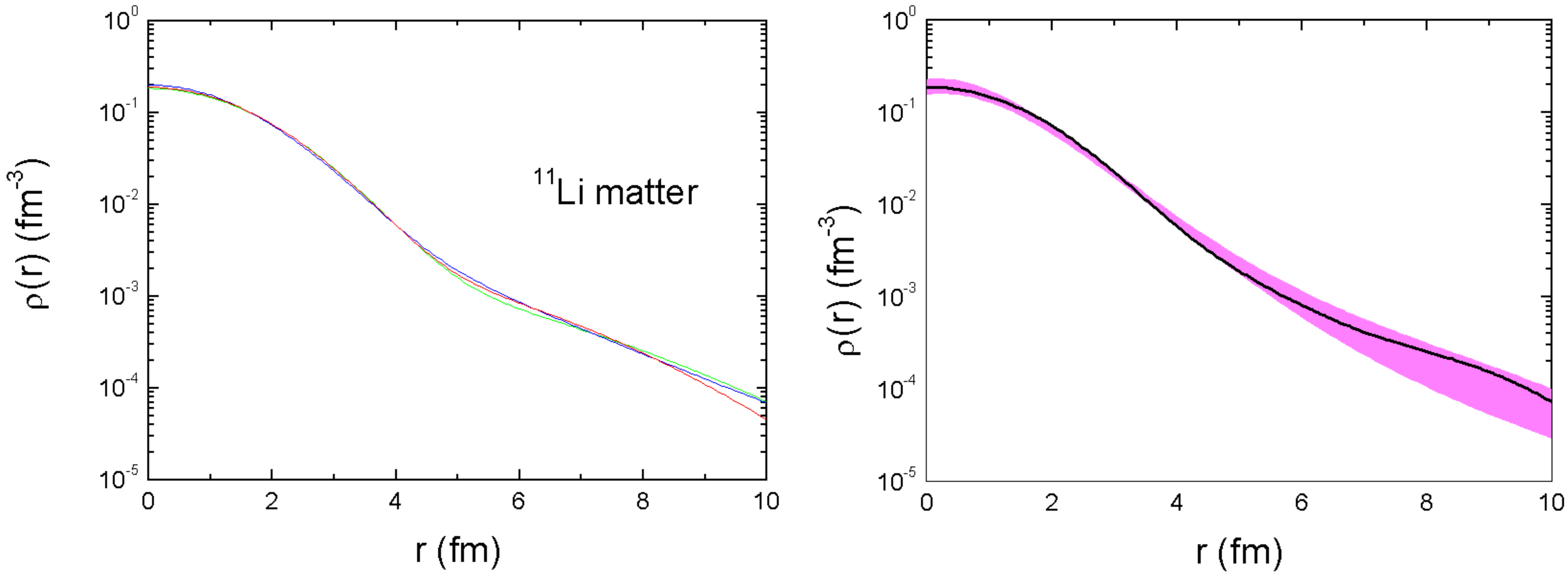
R_m = 3.71 (20) fm

Sensitivity to the Halo-Structure



- clear evidence of halo structure in ^{11}Li
- “normal“ behaviour for ^{8}Li and ^{9}Li
- indication of possible halo-structure in ^{6}Li (due to α+d cluster structure?)

Dependence of the Results on Constraints Implied in the Analysis



phenomenological parametrizations GG, GO without constraints — R_m = 3.71 (20) fm

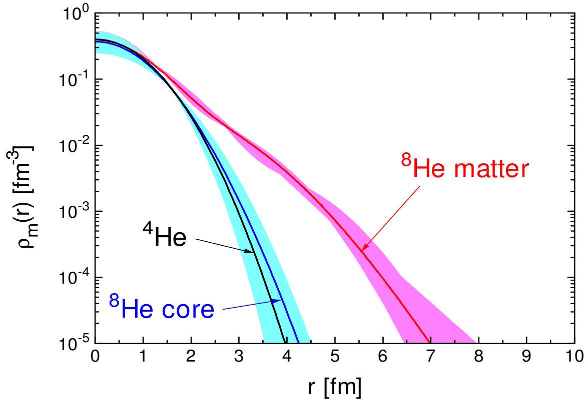
phenomenological parametrization GG + Hankel-function for asymptotic behaviour for r > 6 fm — R_m = 3.72 (19) fm

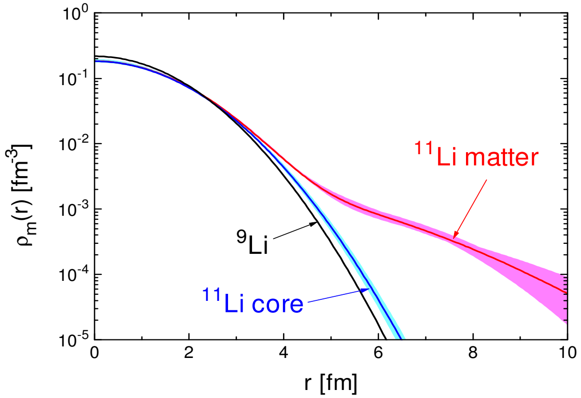
phenomenological parametrization GO with fixed $(1s_{1/2})^2 : (0p_{1/2})^2 = 45 : 55\%$ (from Land-Collaboration: H. Simon et al.) — R_m = 3.53 (19) fm

- model independent SOG analysis — R_m = 3.67 (15) fm

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

nuclear matter distributions:





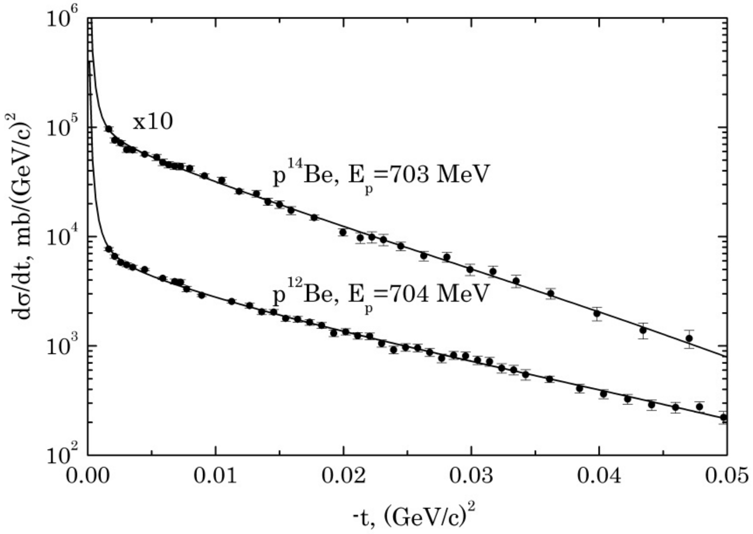
nuclear matter radii:

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)

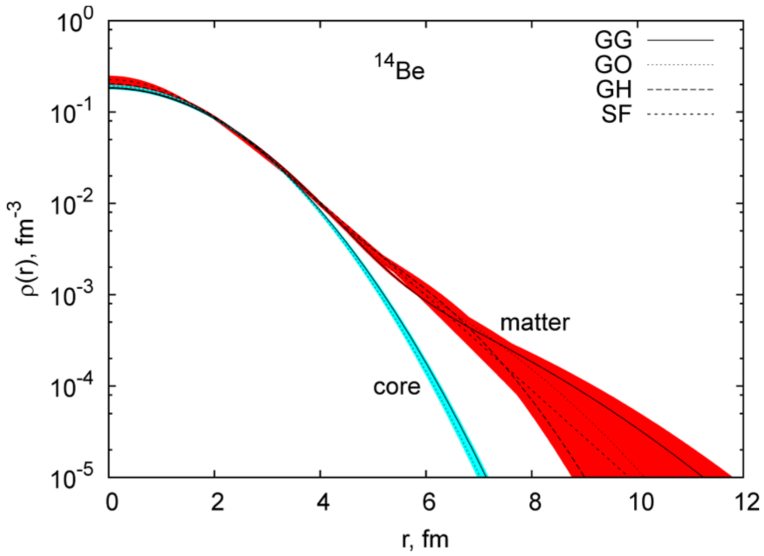
- extended neutron distribution in ^{8}He and ^{11}Li obtained
- size of core, halo and total matter distribution determined with high accuracy
- the picture of a ^{9}Li (^{4}He) core + 2 (4) valence neutron-structure is confirmed for ^{11}Li and ^{8}He

Elastic Proton Scattering from ^{14}Be

differential cross section:



deduced nuclear matter distribution:



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

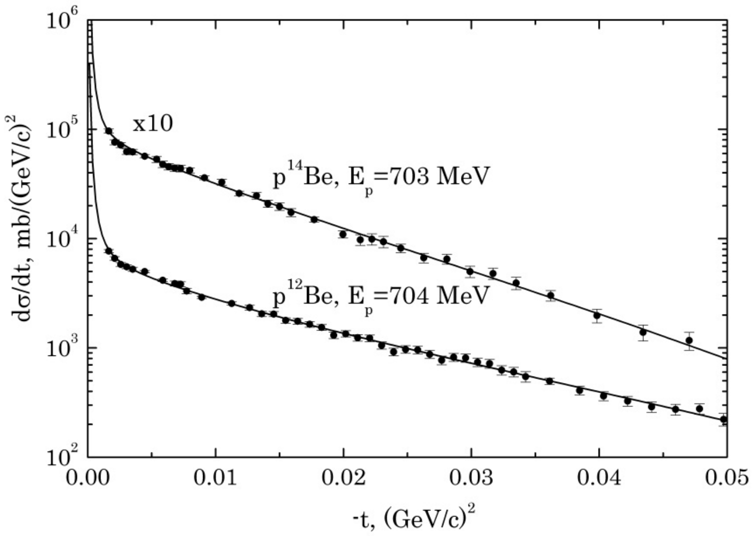
results for ^{14}Be:

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

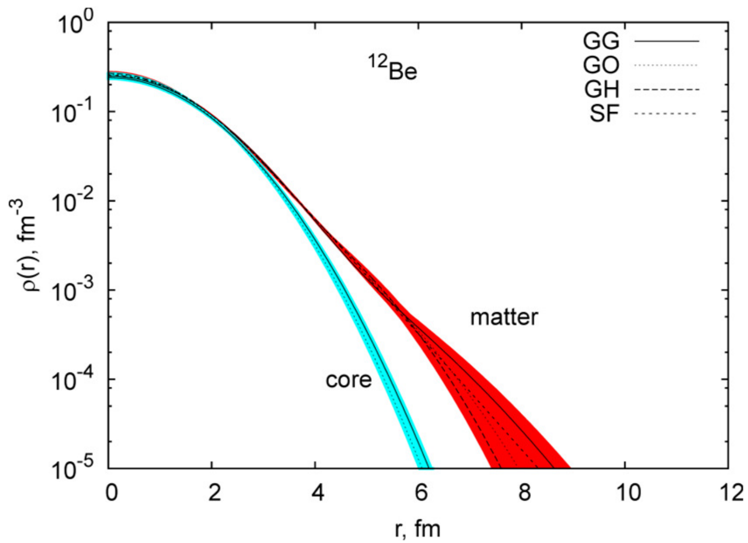
- ^{14}Be exhibits a pronounced core-halo structure
- the picture of a ^{12}Be-core + 2 valence neutron structure is confirmed
- the present data favour a relatively large s-wave component
  (see I. Thompson et. al, Phys. Rev. C53 (1996) 708)

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)

Determination of Neutron Radii and Neutron Skin Sizes

- needs input on proton (charge) distributions

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

  for ^{8}He: Z.-T. Lu et al., Rev. Mod. Phys. 85 (2013) 1383

  for ^{9,11}Li: W. Nörtershäuser et al., Phys. Rev. C 84 (2011) 024307

  for ^{12}Be: A. Krieger et al., Phys. Rev. Lett. 108 (2012) 142501

- 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
^{8}He	2.53 (8)	1.55 (15)	3.22 (14)	1.88 (2)	2.71 (10)	0.83 (10)
^{9}Li	2.44 (6)	--	--	2.11 (5)	2.59 (10)	0.48 (11)
^{11}Li	3.71 (20)	2.53 (3)	6.85 (58)	2.38 (5)	4.10 (26)	1.72 (26)
^{12}Be	2.71 (6)	2.36 (6)	4.00 (28)	2.39(2)	2.86 (9)	0.47 (9)

* R_p from laser spectroscopy, unfolded from proton charge radius

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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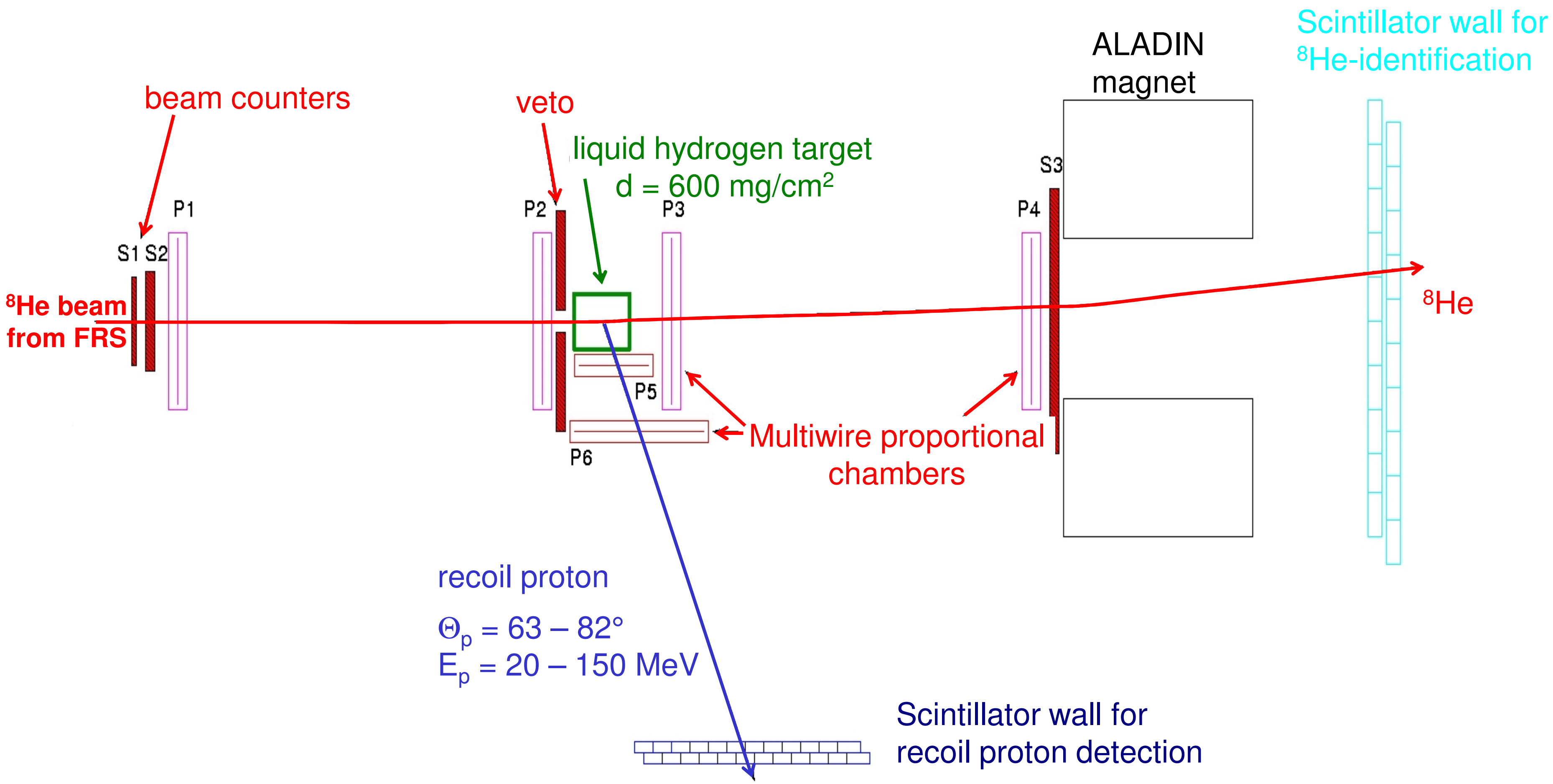
Kurchatov Institute, Moscow, Russia
Institut für Kernchemie, Universität Mainz, Germany
Institut für Kernphysik, TU Darmstadt, Darmstadt, Germany

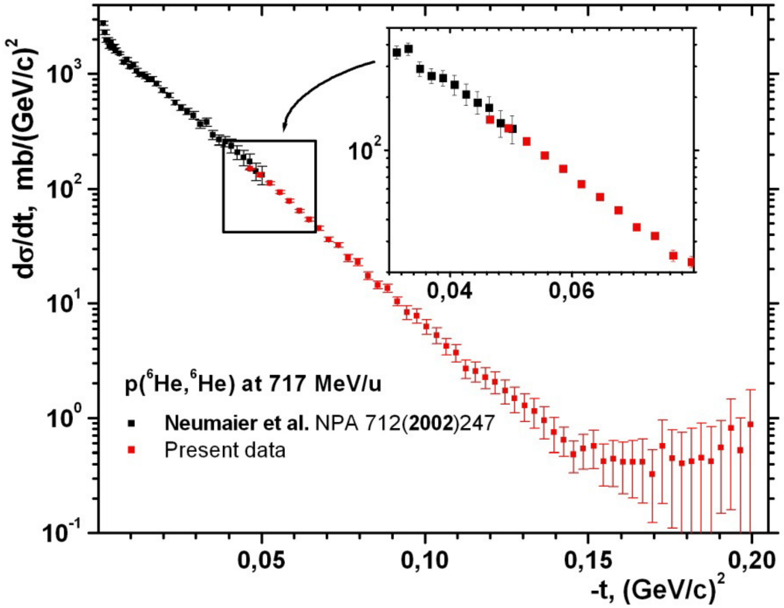
IV. The Structure of Halo Nuclei from Elastic Scattering at Higher Momentum Transfer



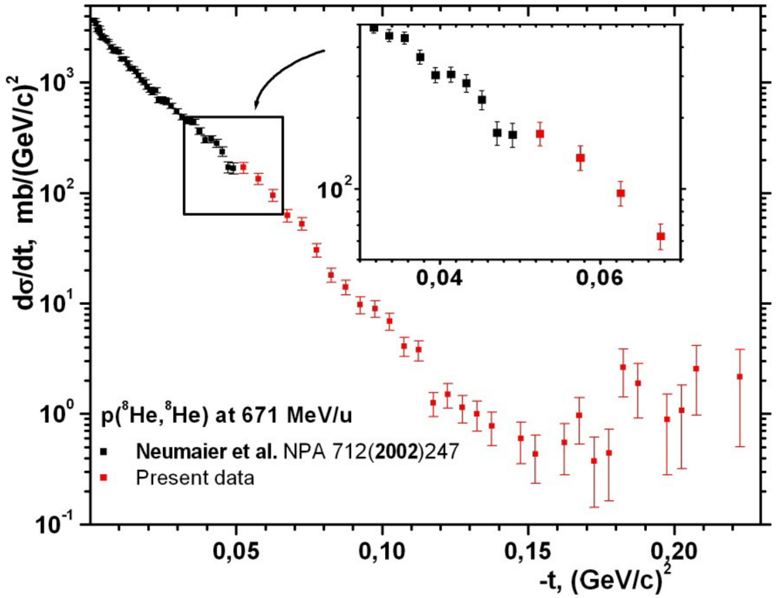
- LH_2 target used for first time in a scattering experiment with RIB's
  ⇒ allows for low background measurements with high luminosity

Experimental Cross Sections for $p^{6,8}He$ Elastic Scattering

$p(^6He,^6He)$ E = 717 MeV/u



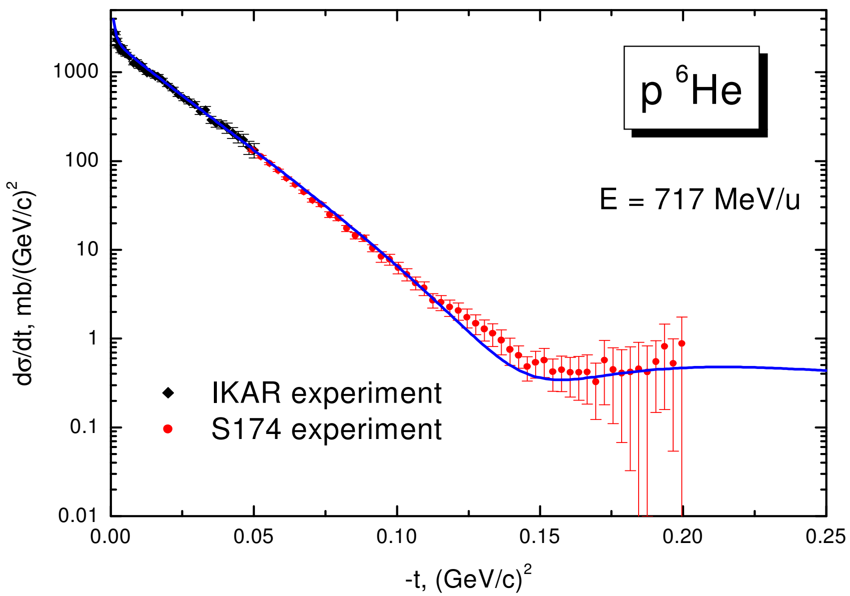
$p(^8He,^8He)$ E = 671 MeV/u

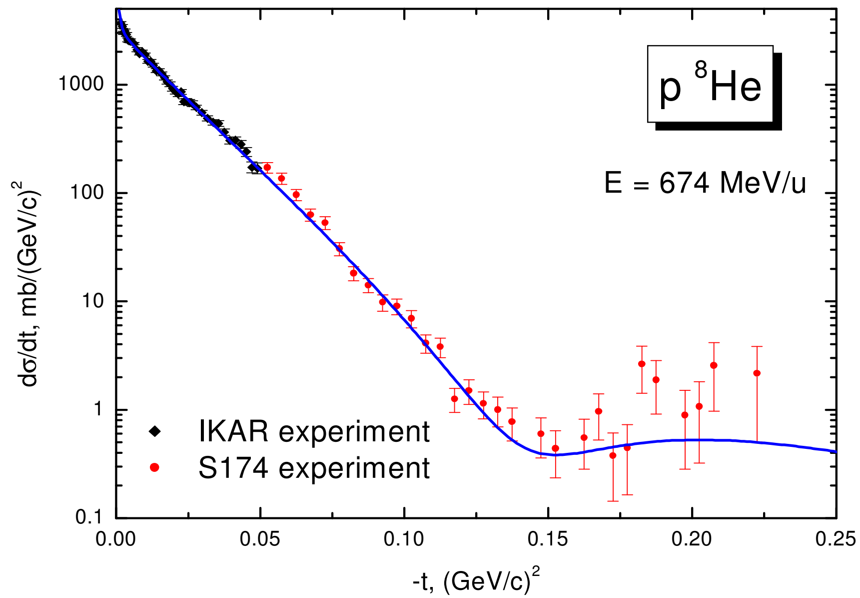


■ IKAR experiment G. D. Alkhazov et al., Nucl. Phys. A712 (2002) 269

■ S174 experiment O. Kiselev et al., Nucl. Instr. Meth. A641 (2011) 72

Experimental Cross Sections for pHe Elastic Scattering

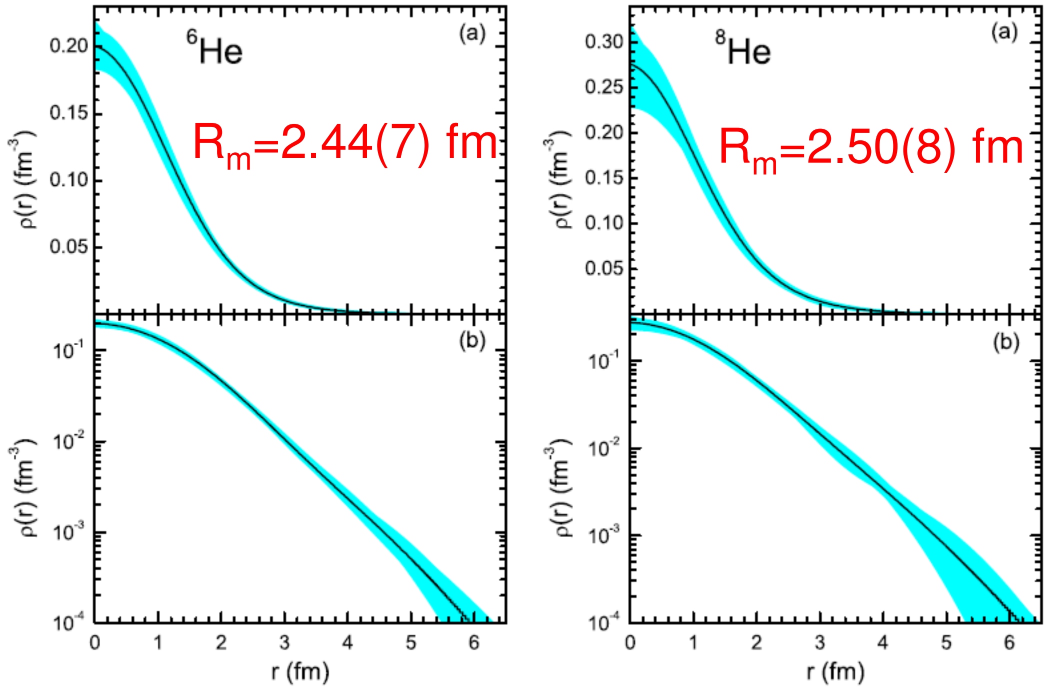




Glauber calculation provides a good description in the whole t-range

Comparison of Results from IKAR and S174 Experiments

combined data (IKAR experiment and S174):
recent analysis including spin-orbit interaction
(X. L. Le et al., Phys. Rev. C92 (2015) 034608)

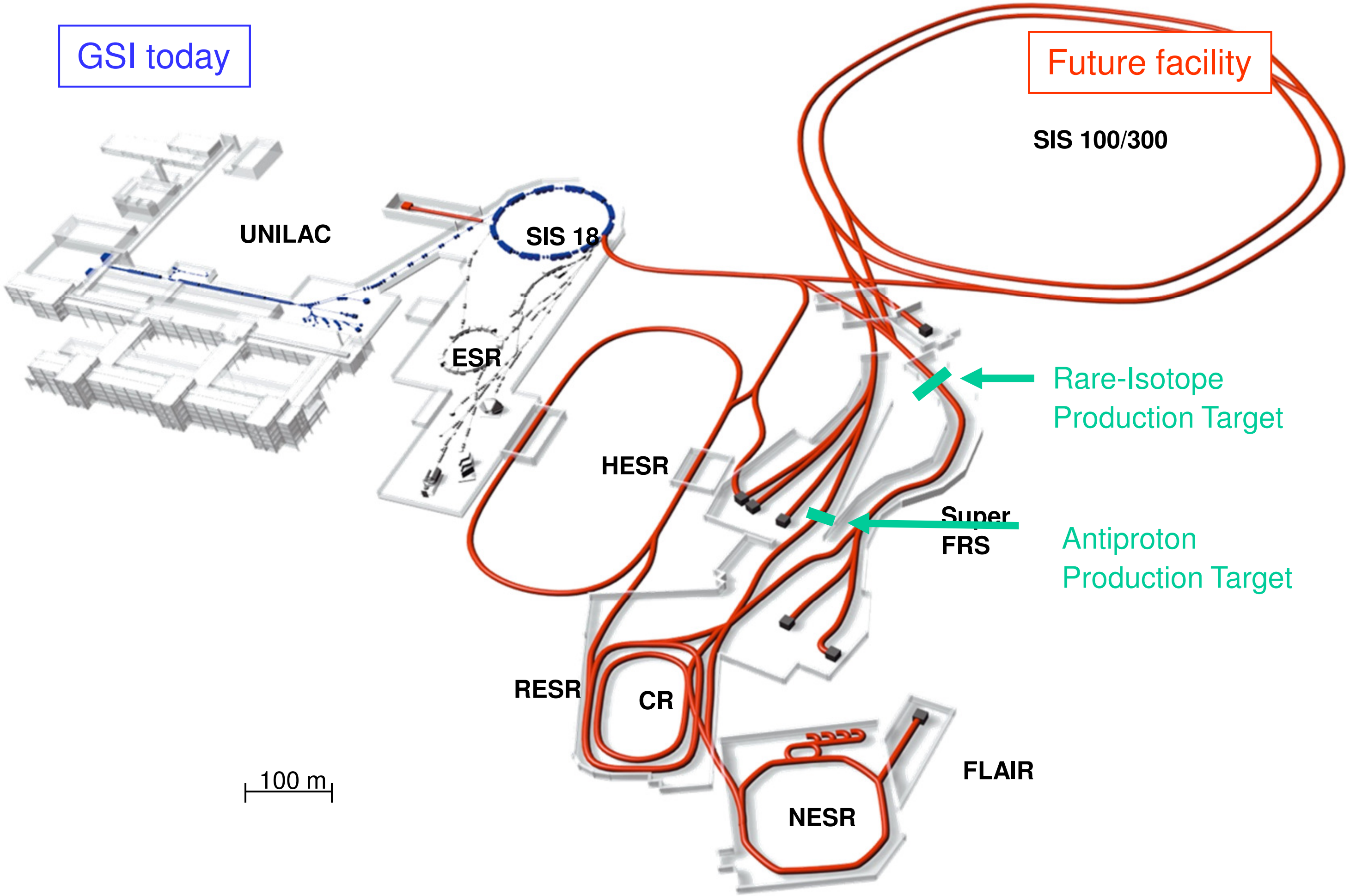


⇒ resulting matter distributions and matter radii fully consistent with results of previous IKAR experiment

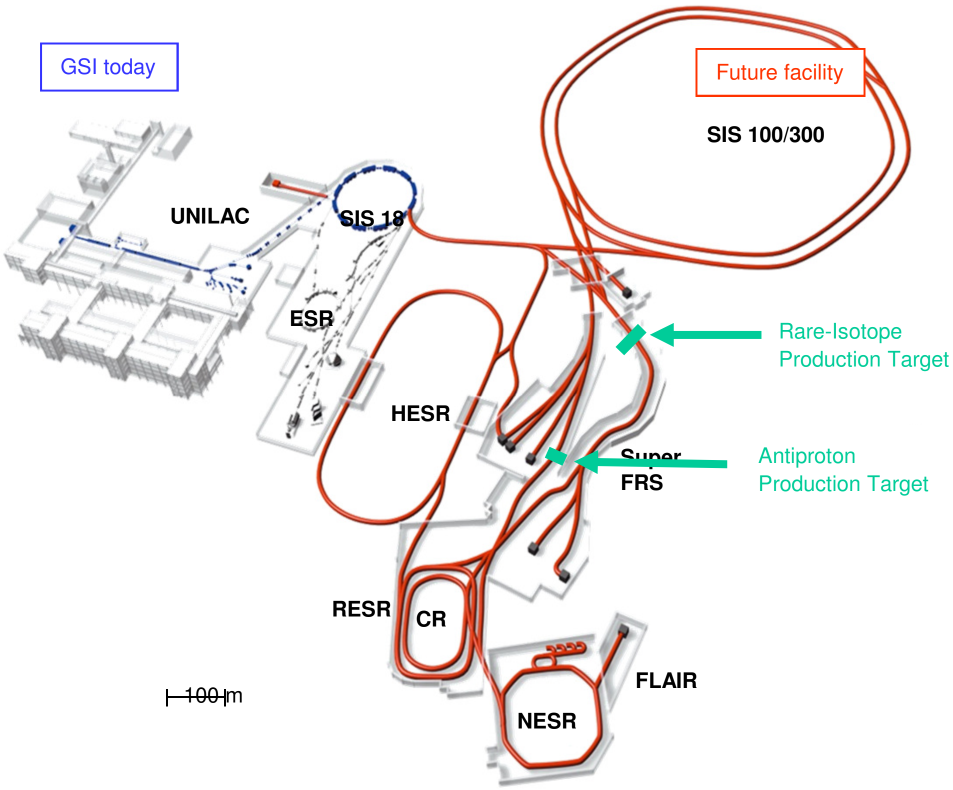
only data at low momentum transfer (IKAR experiment):

^{6}He: R_m=2.45(10) fm ^{8}He: R_m=2.53(8) fm

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
- $2(4)\times10^{13}$/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

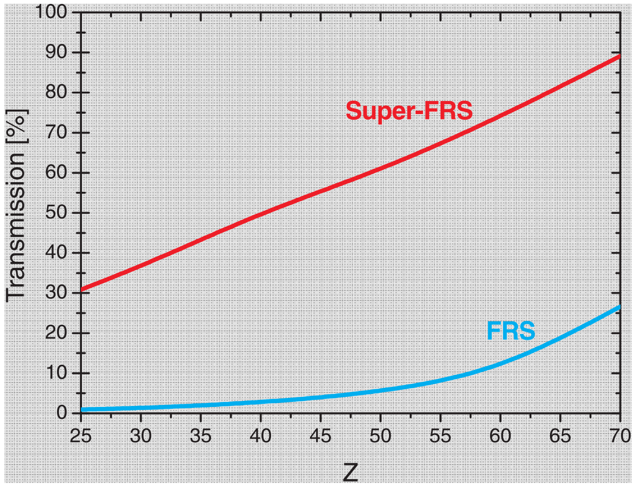
- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

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

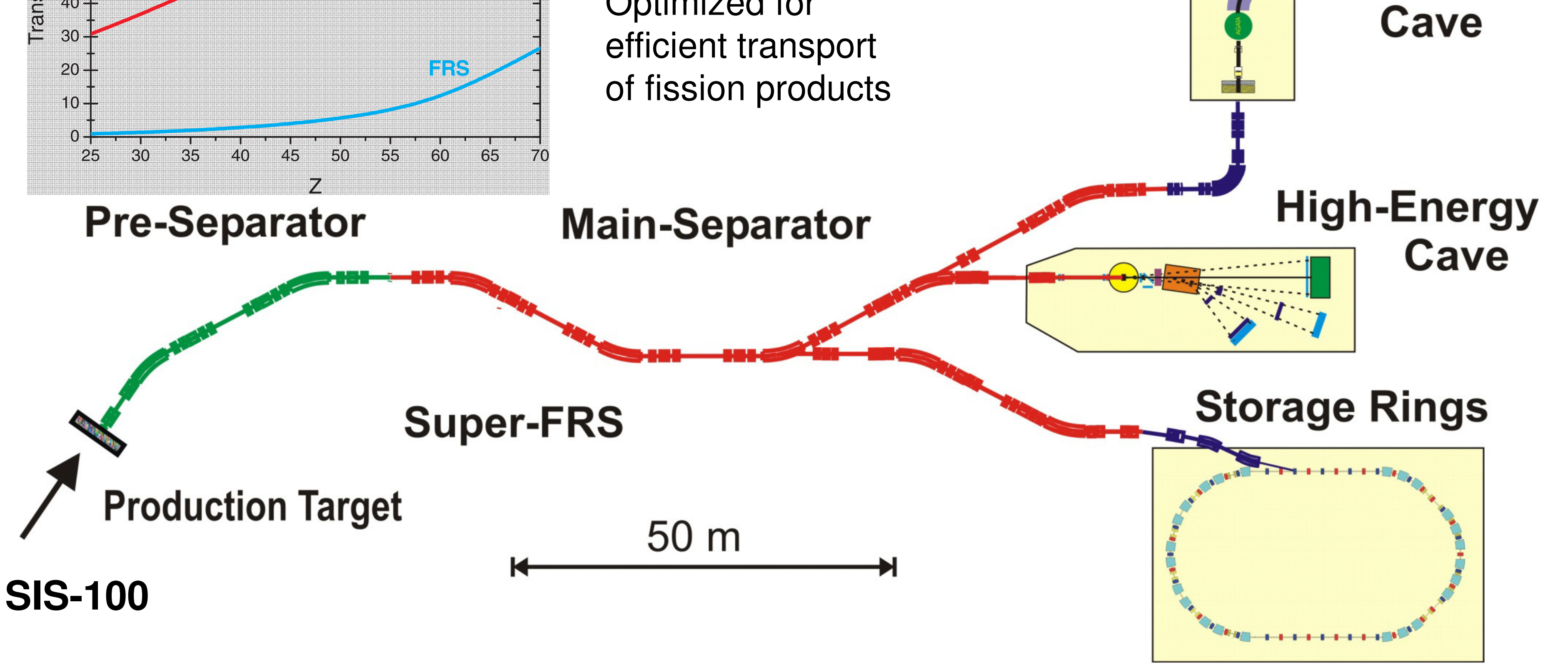
I High intensity primary beams from SIS 100 (e.g. 10^{12} ^{238}U / sec at 1 GeV/u)



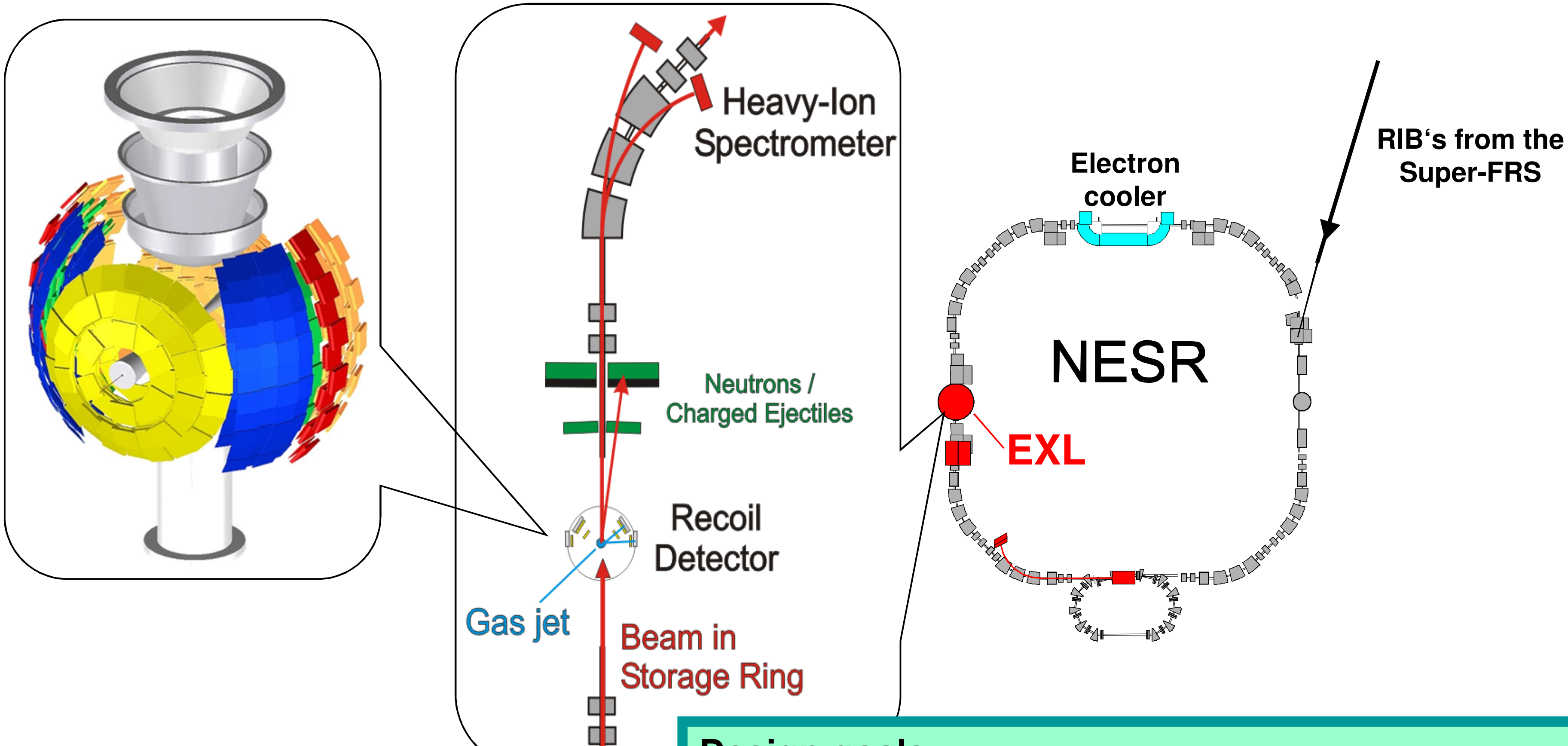
II Superconducting large acceptance Fragmentseparator

III Three experimental areas

Optimized for efficient transport of fission products



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})

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

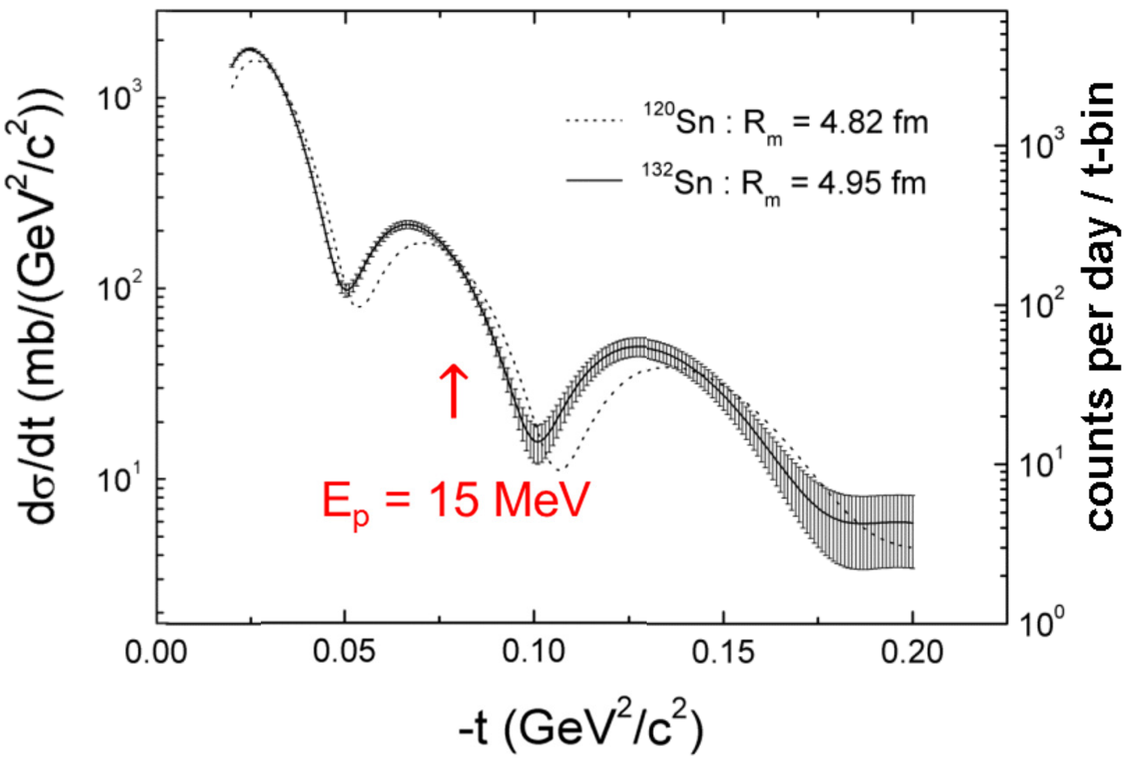
Experiments at very low momentum transfer can only be performed at EXL (except with active targets, but with substantial lower luminosity)

Sensitivity to the Nuclear Matter Radius

reaction: p (^{132}Sn, p), E = 700 MeV/u

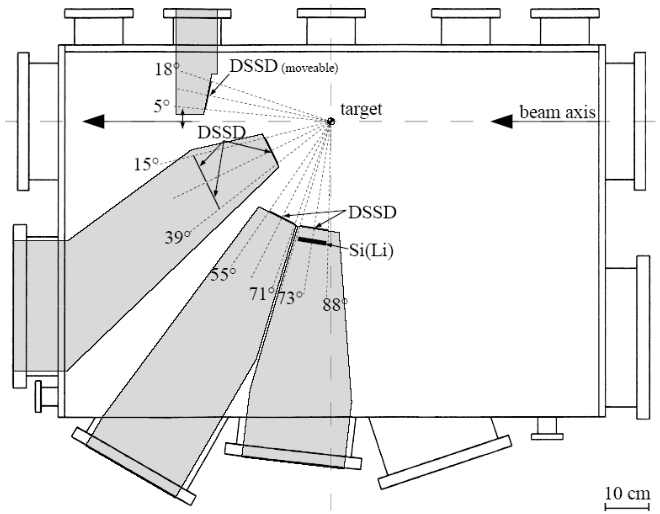
assumed intensity: 5 X 10^3 sec^{-1}

assumed target: active target of 1m at 1 bar



V. 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:

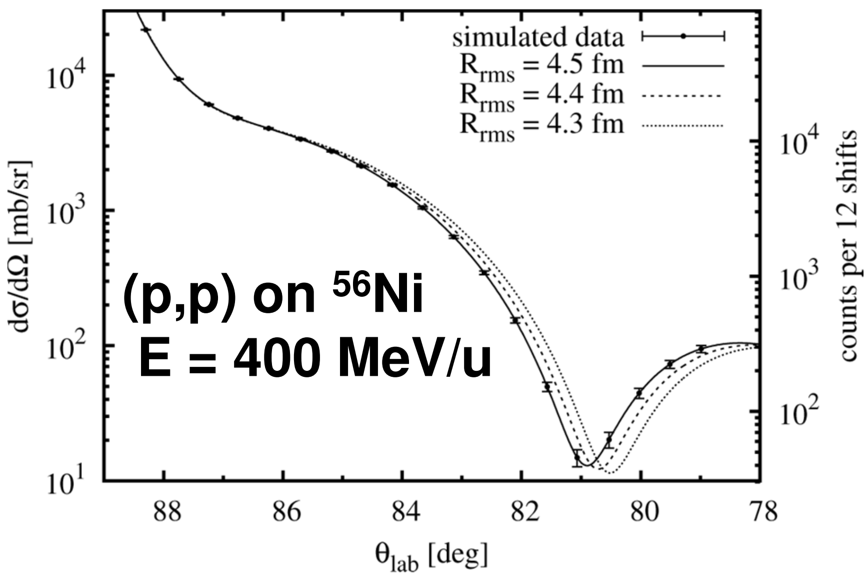
- UHV capability of detector setup
- background conditions in ESR environment at the internal target
- low energy threshold
- beam and target performance

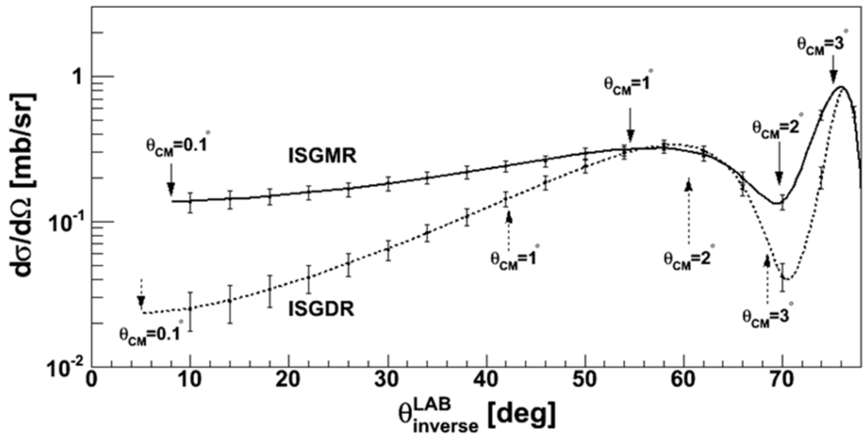
reactions with ^{56}Ni:

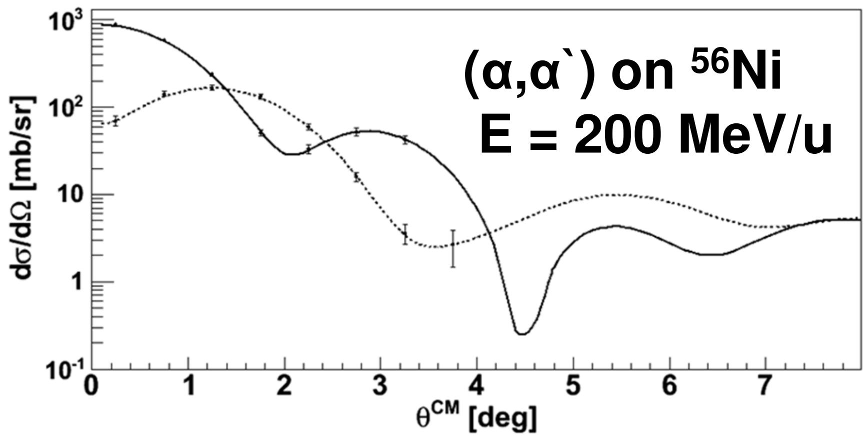
^{56}Ni: doubly magic nucleus!!

- (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





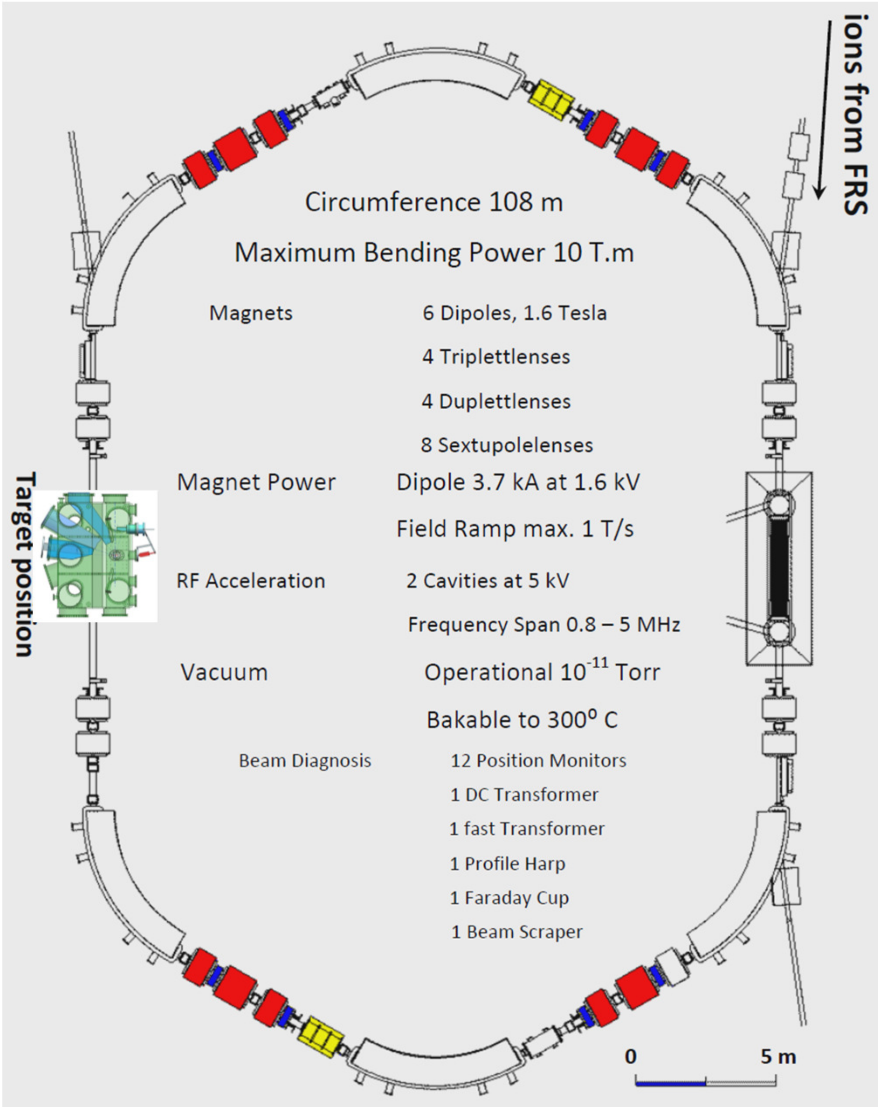


4 days with L = 10^{25} cm^{-2} sec^{-1}
recoil energies: 1 – 45 MeV

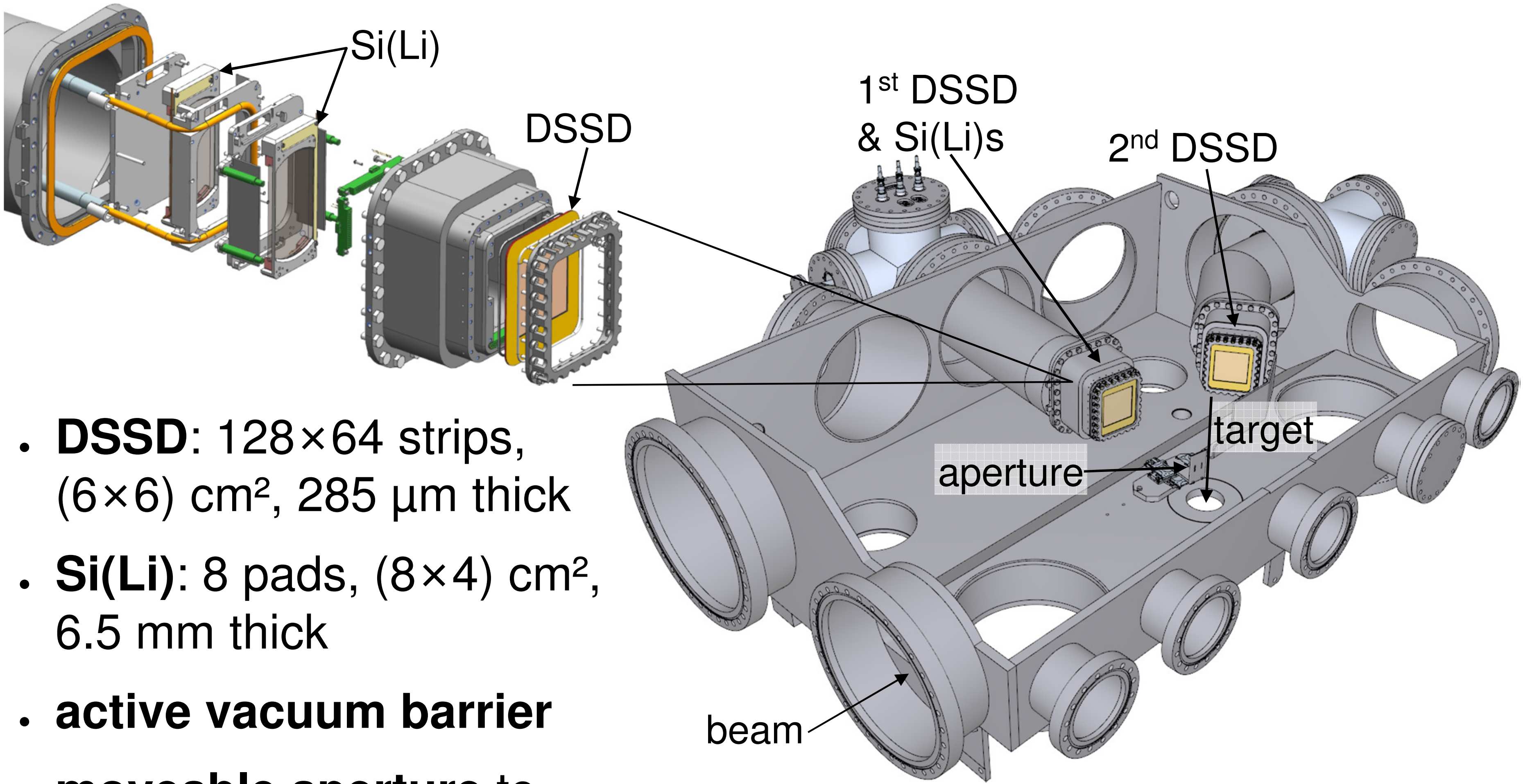
14 days with L = 10^{25} cm^{-2} sec^{-1}
recoil energies: 200 – 700 keV

<u>needed: </u>large solid angle detectors with low threshold and large dynamic range

Setup at the ESR Storage Ring



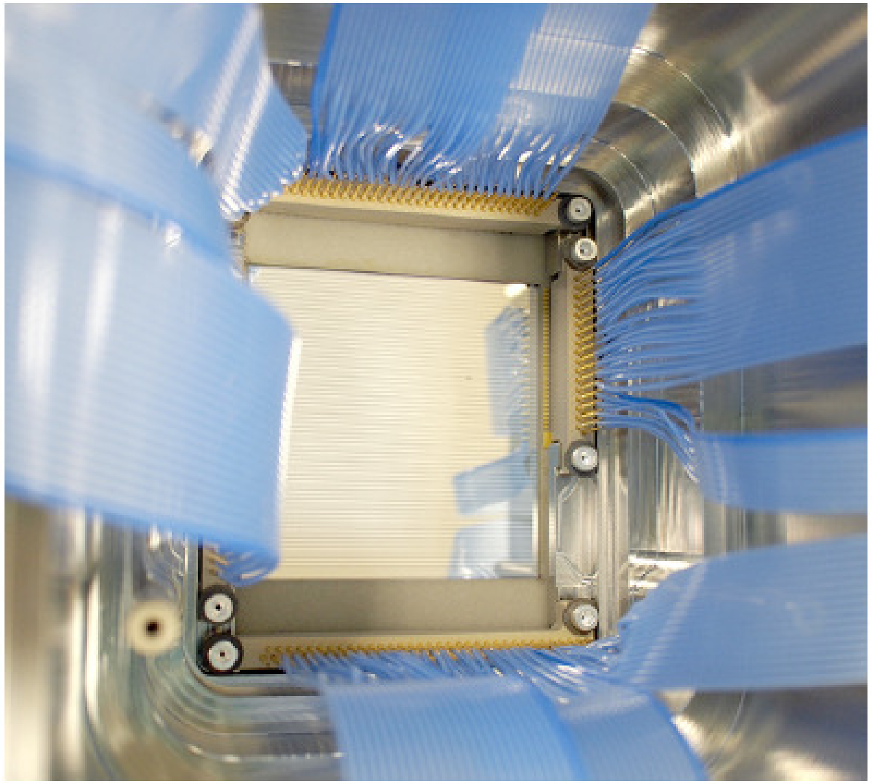
Experimental Concept for the E105 Experiment



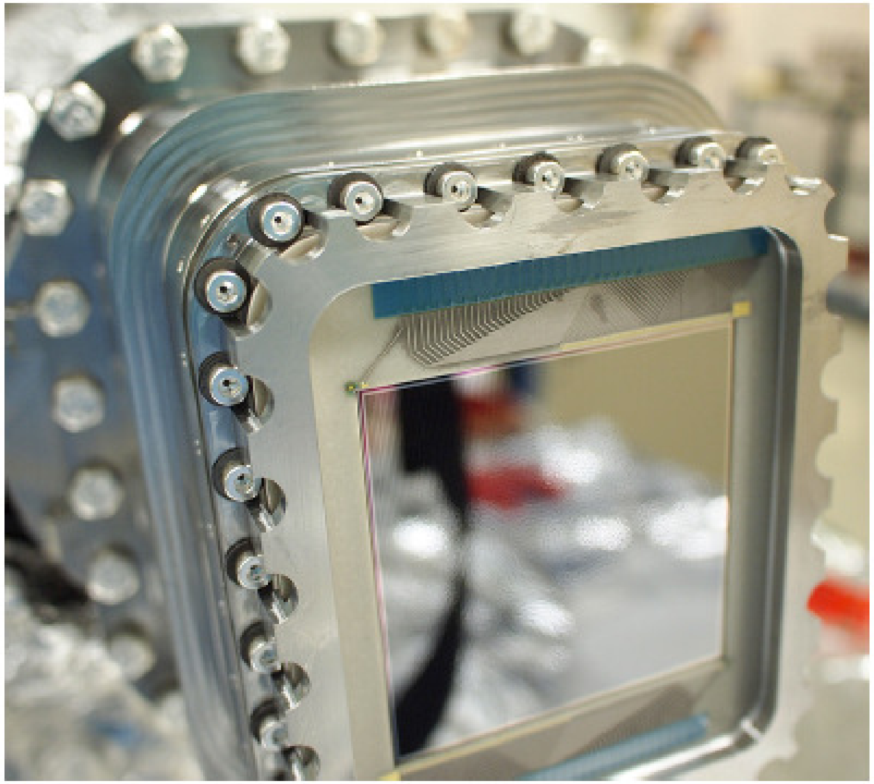
- **DSSD**: 128×64 strips, (6×6) cm², 285 µm thick
- **Si(Li)**: 8 pads, (8×4) cm², 6.5 mm thick
- **active vacuum barrier**
- **moveable aperture** to improve angular resolution

Experimental Concept for the E105 Experiment

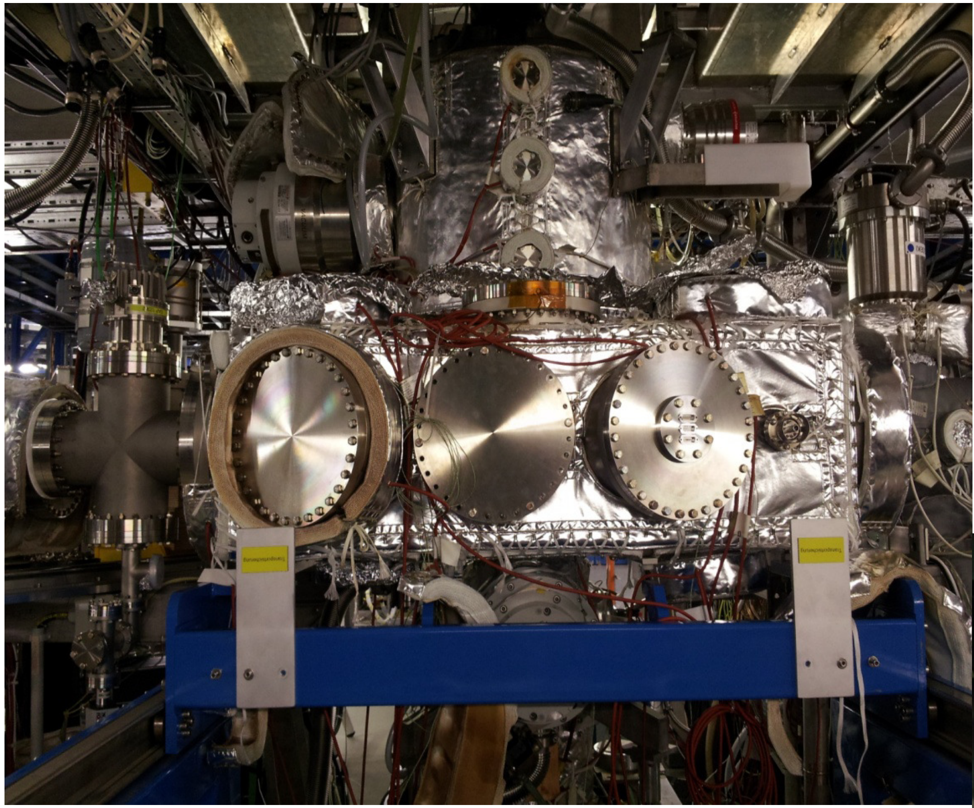
- Auxilliary vacuum side



- Ultra-high vacuum side

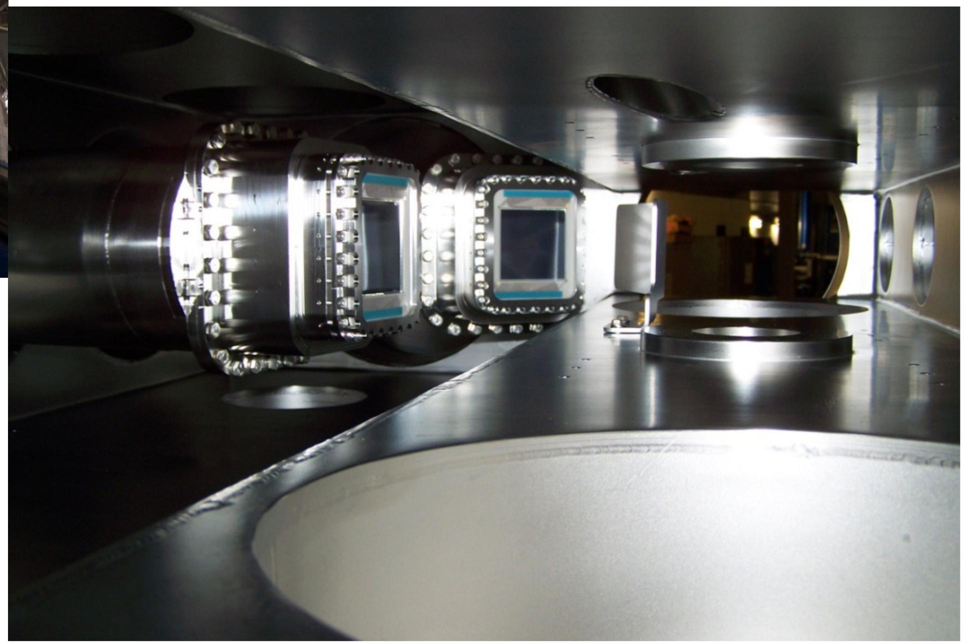


Experimental Setup at the ESR



Scattering Chamber mounted at the Internal Target of the ESR

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



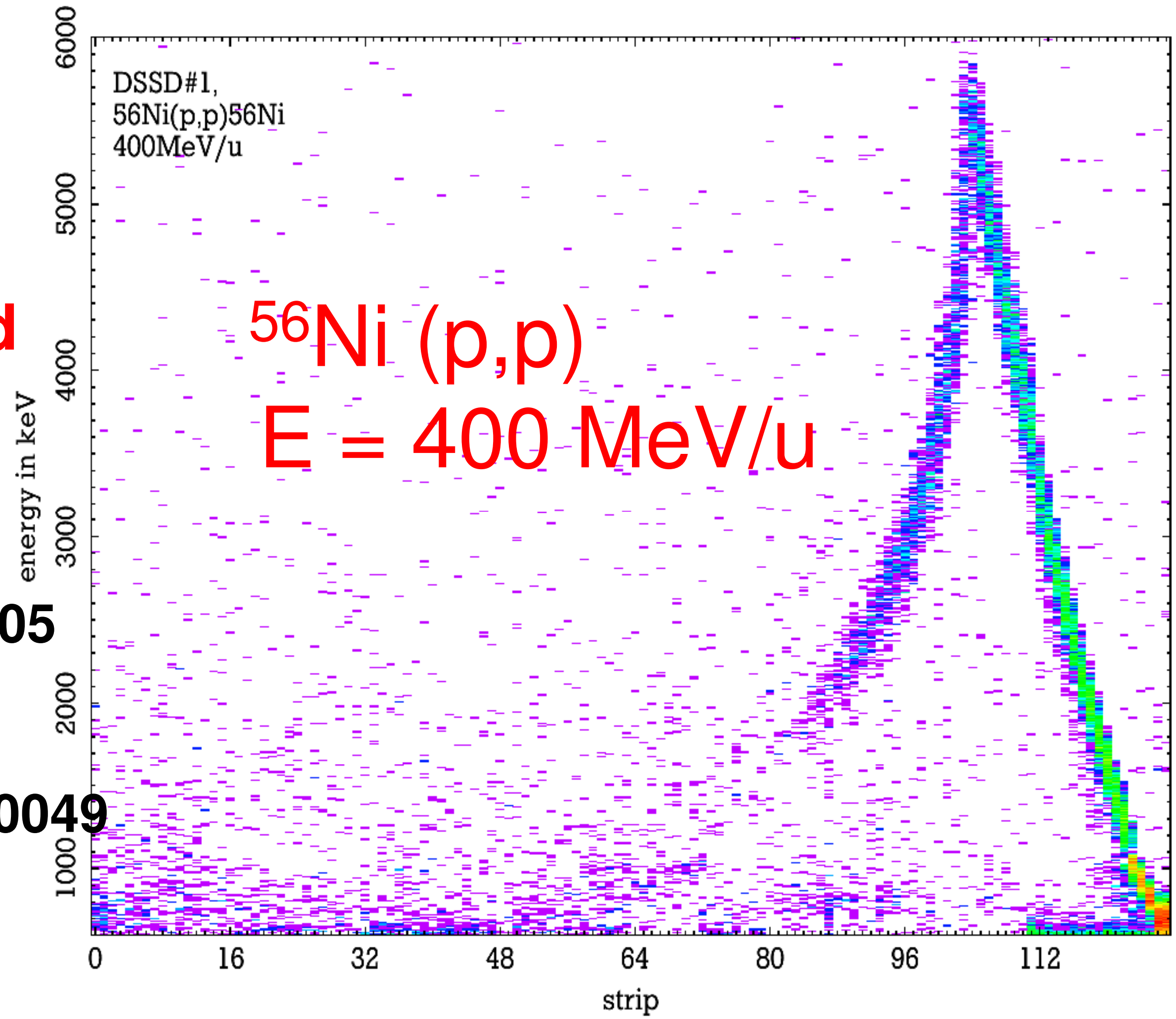
First Results with Radioactive Beam

25. 10. 2012:

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

M. von Schmid et al., Phys. Scr. T166 (2015) 014005

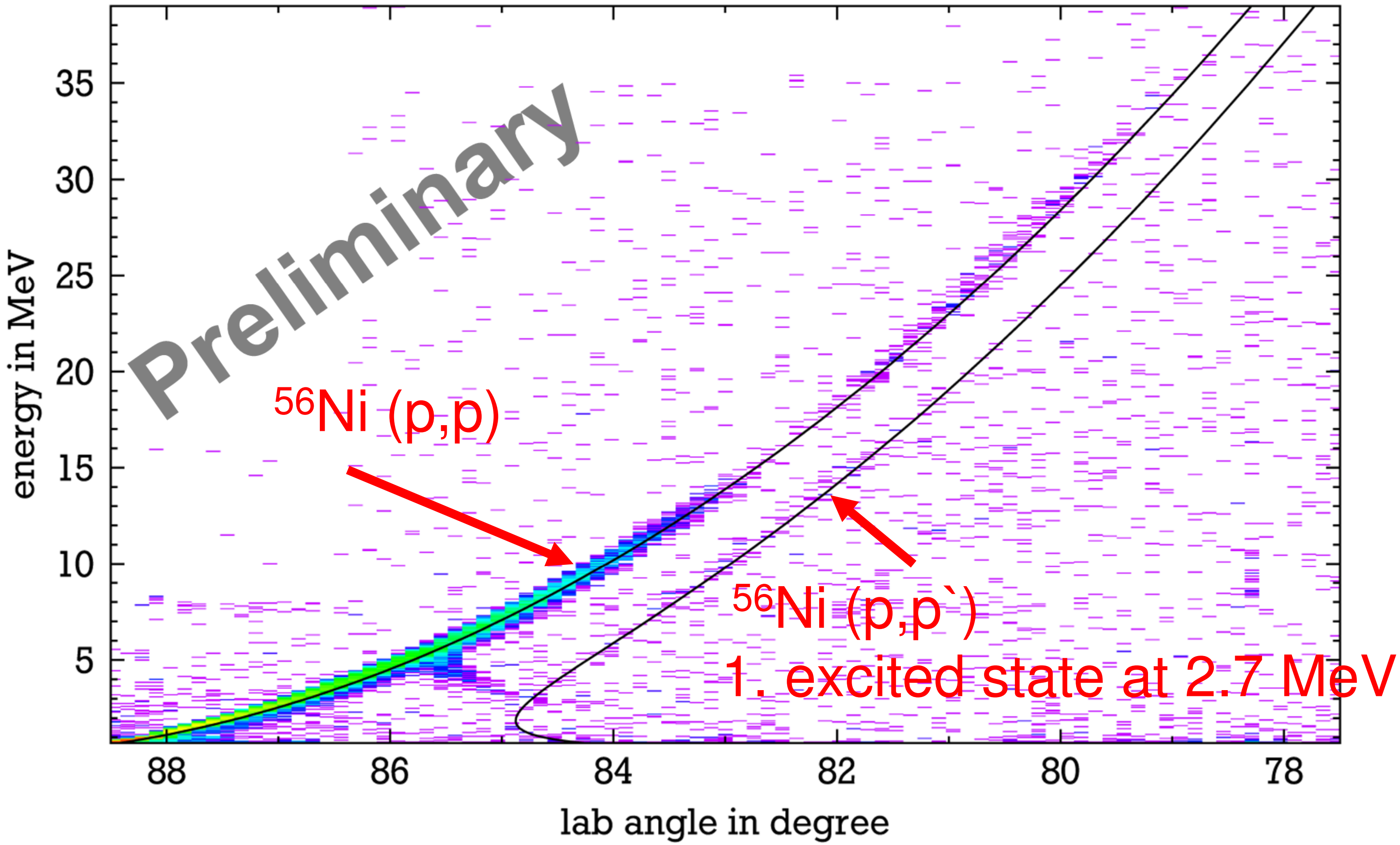
P. Egelhof et al., JPS Conf. Proc. 6 (2015) 020049



Θ_{Lab} = 72° .... 88°

First Results with Radioactive Beam

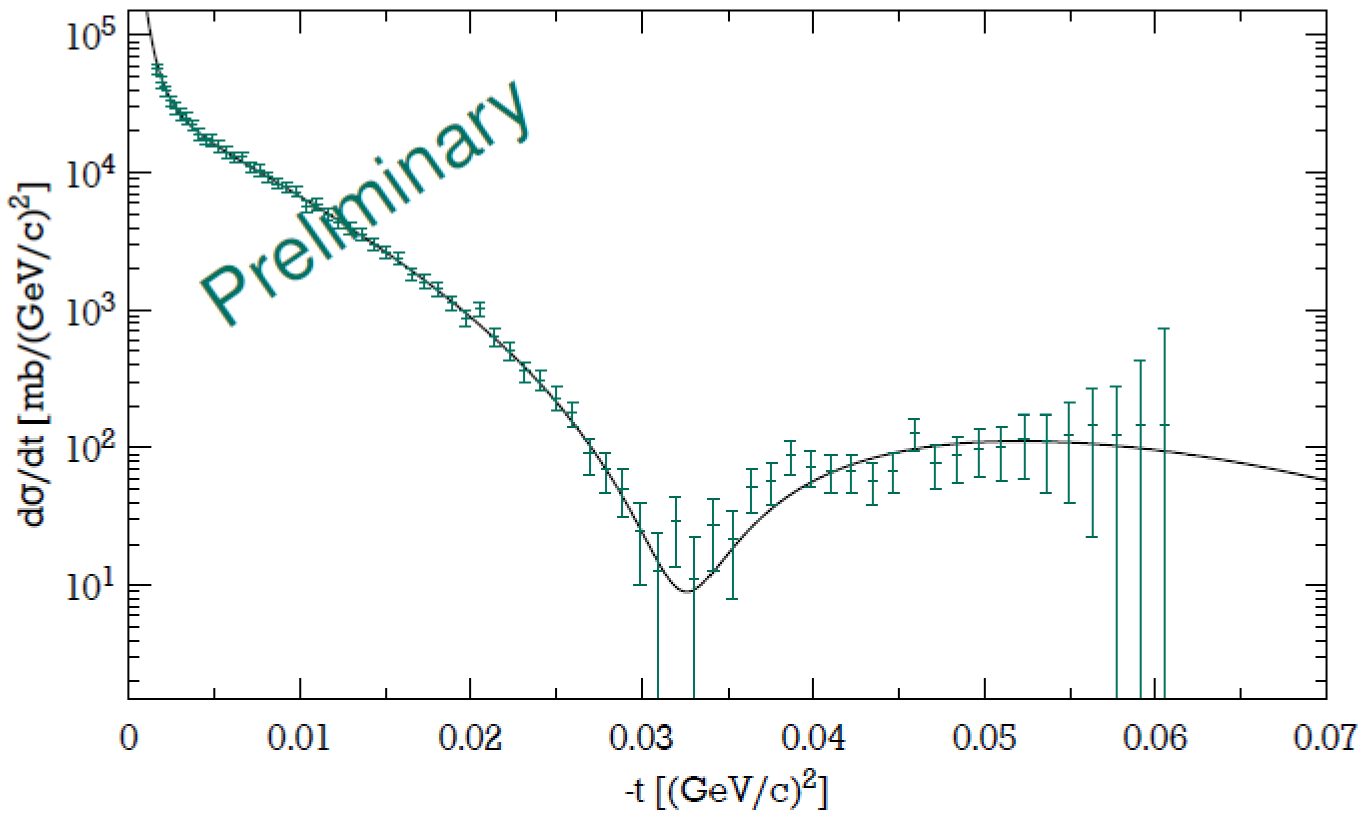
^{56}Ni(p,p\`), E = 400 MeV/u   Identification of Inelastic Scattering



First Results with Radioactive Beam

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

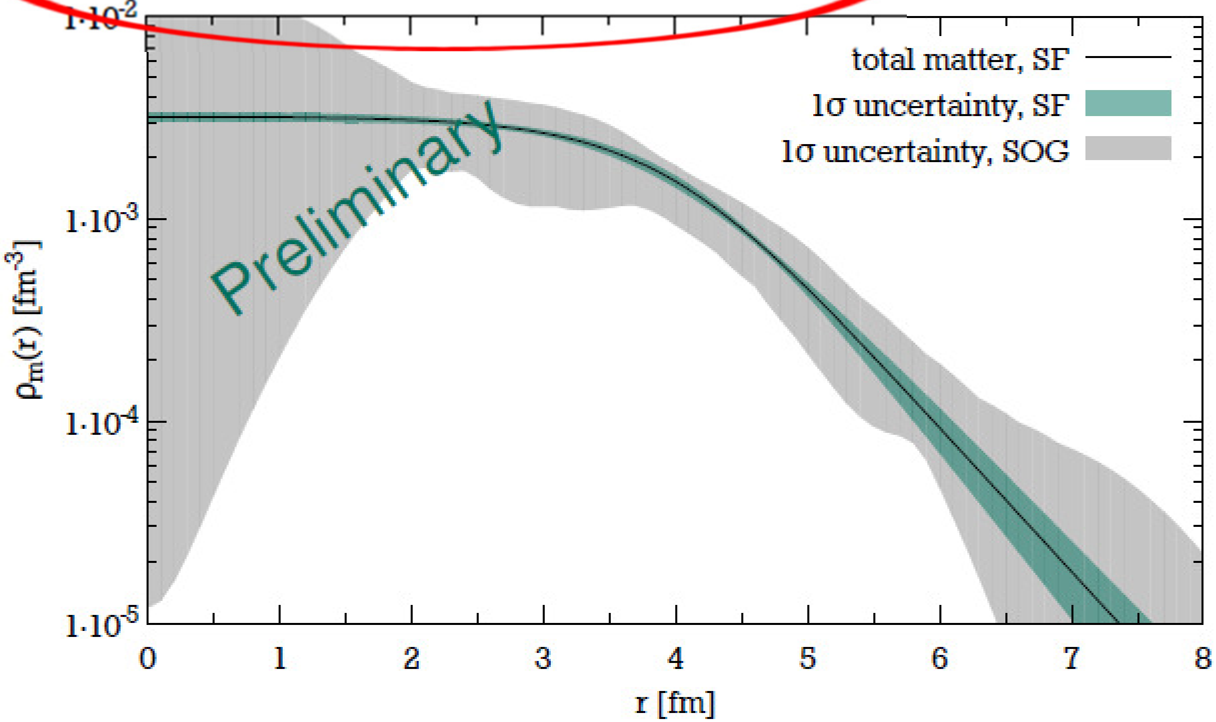
Cross Section fitted using the Glauber Theory



M. v. Schmid, PHD thesis 2015

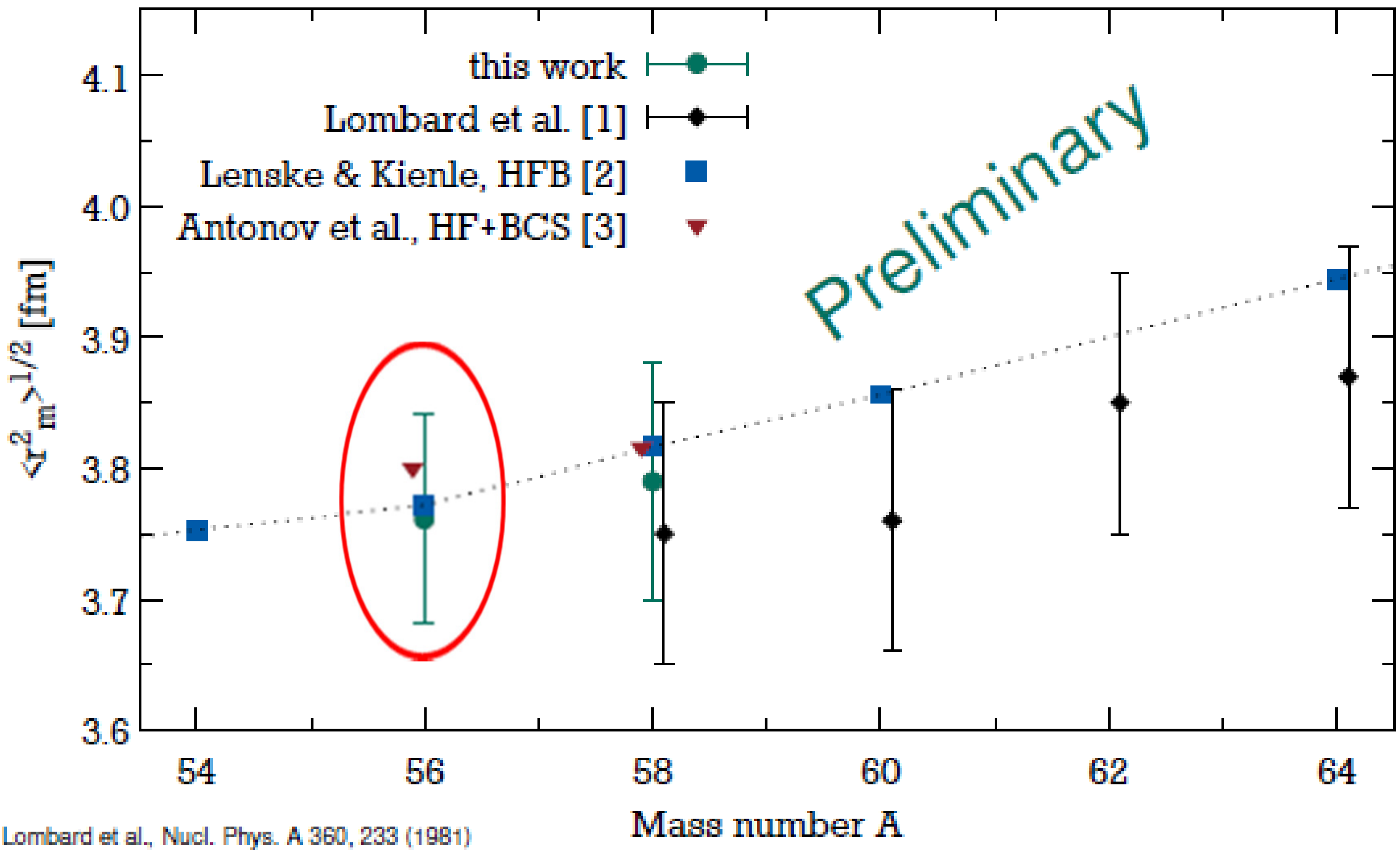
Nuclear Matter Distribution of ^{56}Ni

RMS matter radius: $\langle r_m^2 \rangle^{1/2} = (3.76 \pm 0.08)$ fm



M. v. Schmid, PHD thesis 2015

Nuclear Matter Radii in Ni Isotopes



[1] R.M. Lombard et al., Nucl. Phys. A 360, 233 (1981)
[2] H. Lenske and P. Kienle, Phys. Lett. B 647, 82 (2007)
[3] A.N. Antonov et al., Phys. Rev. C 72, 044307 (2005)

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]

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Statistical and Systematical Uncertainties on the Matter Radius R_m

example: ^{8}He (from: G. D. Alkhazov et al., Nucl. Phys. A712 (2002) 269)

Nucleus	R_m (fm)	Total errors (fm)	Error contributions to R_m from different sources, fm					
			Stat. errors	Model uncertainties[a]	σ_{pN}	ϵ_{pN}	β_{pN}	t-scale
^{8}He	2.45	0.07	0.04	0.02	0.01	0.02	0.03	0.02

[a] Deviations from the average values of the matter radii R_m deduced with the four model densities individually.

systematical uncertainties on R_m: $\Delta R_m \sim 0.04$ fm

VI. Which Accuracy on the Neutron Skin can be finally reached?

systematical uncertainties on R_m: $\Delta R_m \sim 0.04$ fm

systematical uncertainties on R_p: $\Delta R_p \sim 0.02$ fm $\Rightarrow \Delta \delta_{np} \sim 0.05$ fm

(from Laser Spectroscopy, SCRIT, ELISE...)

additional contributions:

- statistical uncertainty
- approximations (Eikonal, Adiabatic, ...)
- nucleon correlations

important ingredients:

- calibration to neutron skin measurements with other methods (stable isotopes)
- resolve inelastic from elastic scattering (storage ring experiments)
- discriminate isomeric contributions in exotic beams (storage ring experiments)
- good statistics (FAIR intensities)

Summary and Conclusions

- elastic proton scattering at intermediate energies is a powerful tool to study nuclear matter distributions of exotic nuclei
  $\Rightarrow$ the active target IKAR was successfully applied for low q measurements
  $\Rightarrow$ data on ^{6,8}He, ^{6,8,9,11}Li , ^{12,14}Be, ^{8}B and ^{17}C were obtained (in a direct way)

- the absolute differential cross sections allow to deduce:
  $\Rightarrow$ precise "model independent" nuclear matter radii
  $\Rightarrow$ the radial shape of nuclear matter distributions

- a combination with data from elastic electron scattering allows to determine the radial shape neutron skins

- in future powerfull experimental methods (EXL, ACTAR, ELISe at FAIR, SCRIT at RIKEN) will allow to reach high accuracy ($\Delta (R_n - R_p) \leq 0.05$ fm) data on neutron skins