EXL

EXotic nuclei studied in Light-ion induced reactions at the NESR storage ring

A unique opportunity at the future FAIR facility

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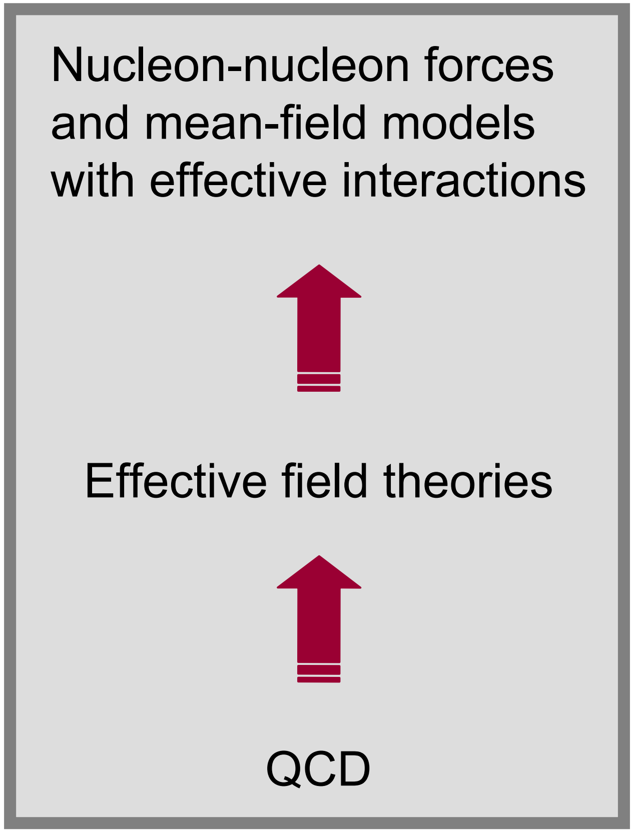
FAIR – UK Meeting, Daresbury, January 25-26, 2006

The Nuclear Chart: Theoretical Perspective

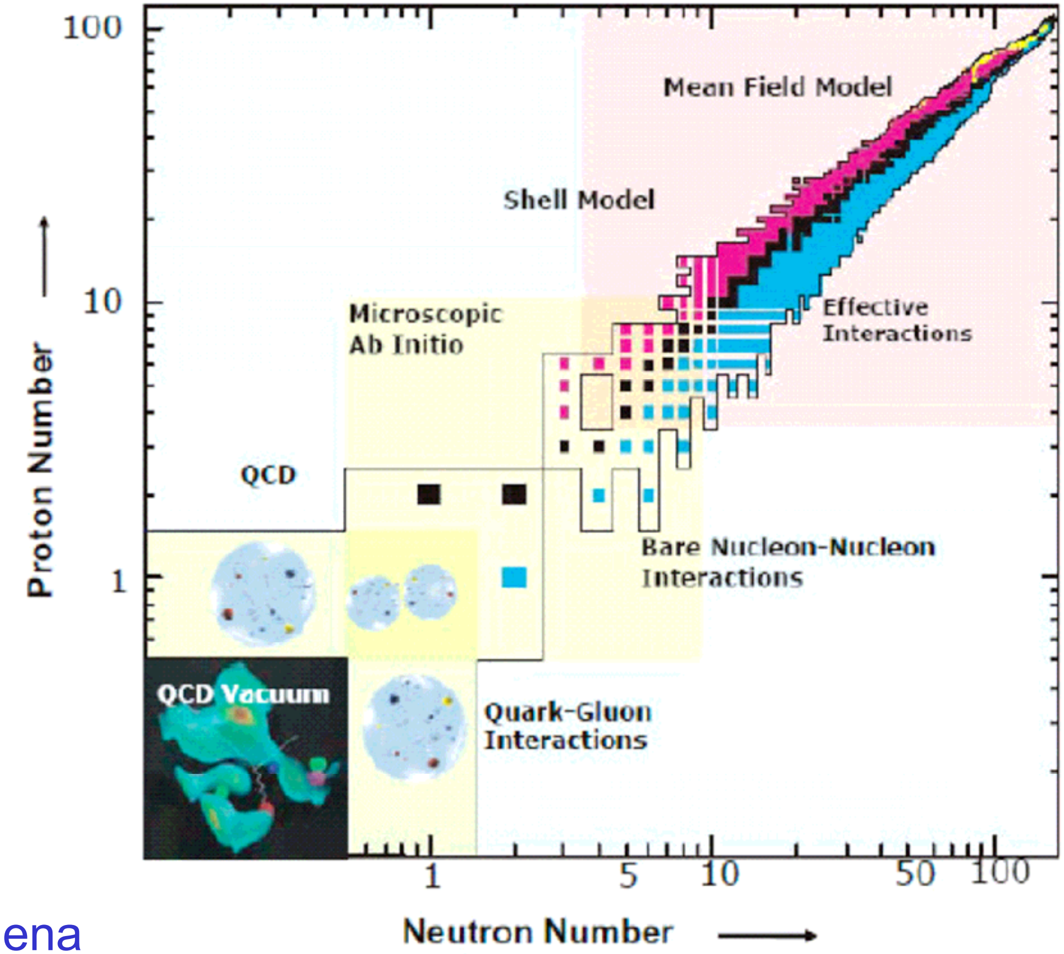
Tackling the nuclear many-body problem…



Nucleon-nucleon forces and mean-field models with effective interactions

Effective field theories

QCD



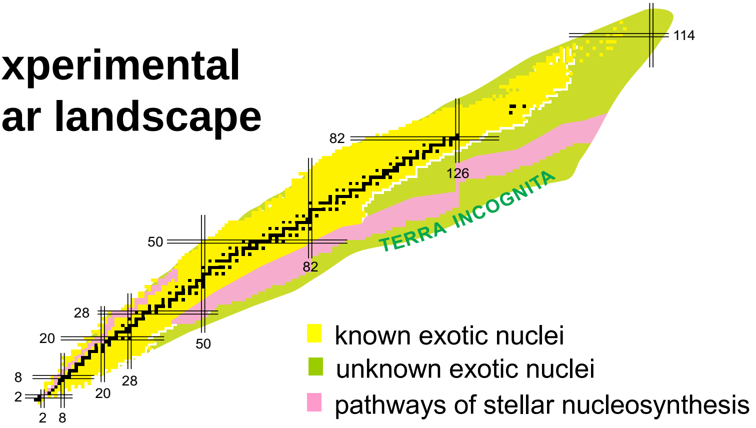
Experimental data and new phenomena challenge our theoretical descriptions of the nucleus

EXotic nuclei studied in Light-ion induced reactions at the NESR storage ring

❖ Key physics issues

- Matter distributions (halo, skin…)
- Single-particle structure evolution (magic numbers, shell gaps, spectroscopic factors)
- NN correlations, clusters
- New collective modes (different deformations for p and n, giant resonances strengths)
- Astrophysical r and rp processes (GT, capture…)
- In-medium interactions in asymmetric and low-density matter

The experimental nuclear landscape



❖ Light-ion scattering

Elastic (p,p), (α,α) …

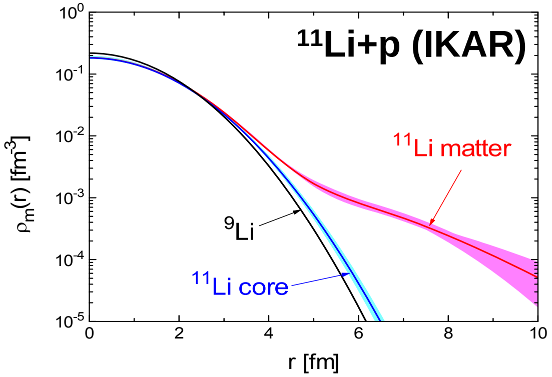
Inelastic (p,p’), $(\alpha,\alpha’)$ ...

Charge exchange (p,n), (^{3}He,t), (d,^{2}He) …

Quasi-free (p,pn), (p,2p), (p,pα) …

Transfer (p,t), (p,^{3}He), (p,d), (d,p) …

~ 15 … ~ 740 MeV/nucleon



Theory: P.-G. Reinhard

<u>Ex:</u> 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)

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

- GMR gives access to nuclear compressibility

  $$K_{nm}\,(Z,N) \;\sim\; \rho_0^2\, d^2(E/A)\,/\,d\rho^2\,|\,\rho_0$$

  ⇨ Key parameter of EOS

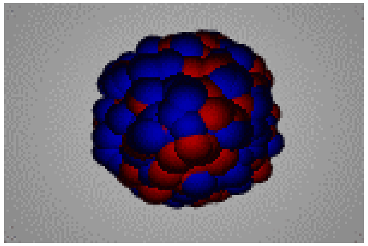
- Investigation of isotopic chains arround ^{132}Sn, ^{56}Ni, … with high $\delta = (N\text{-}Z)/A$

  ⇨ Disentangle different contributions to

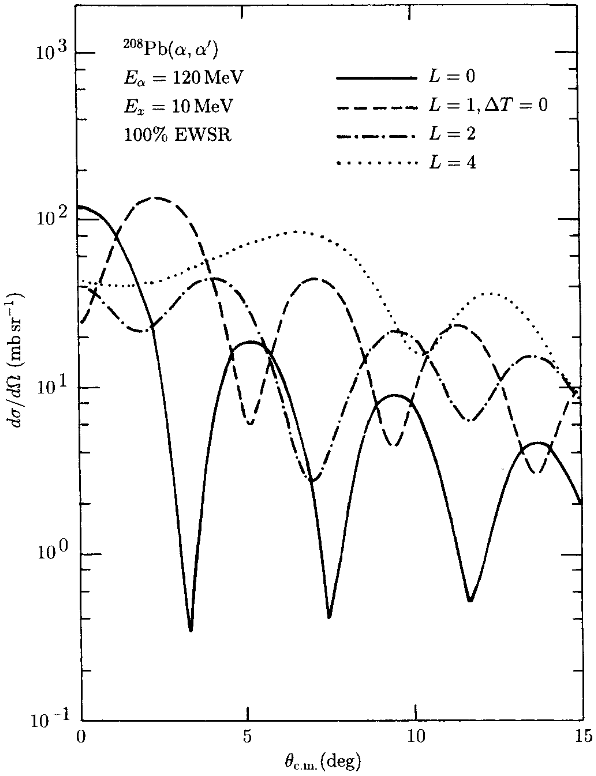
  $$K_A \;=\; K_{vol} \;+ K_{surf}\, A^{-1/3} \;+ K_{sym}\,((N\text{-}Z)/A)^2 + \;\ldots$$

- Investigation of new collective modes

  ⇨ Breathing mode of neutron skin



isoscalar



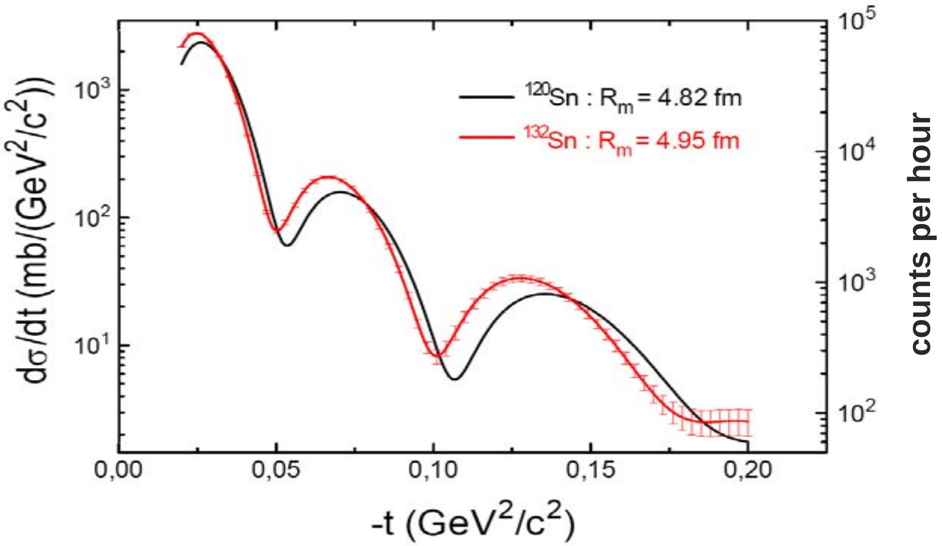
Experimental conditions to investigate the GMR

⇨ (α,α') inelastic scattering
at very low momentum transfer

Feasibility Study with EXL

Elastic proton scattering ^{132}Sn (Matter Distribution)

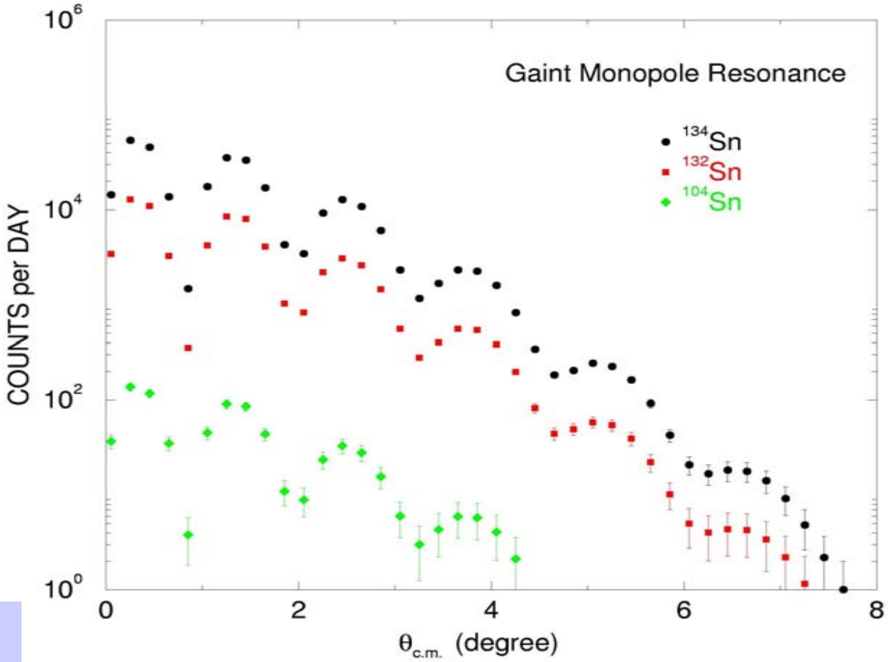
Skin and haloes in heavy neutron-rich nuclei, nuclear potential parameters



High sensitivity of the method
(simulation of experimental conditions as expected at the NESR with a luminosity of 10^{28} cm^{-2} s^{-1})

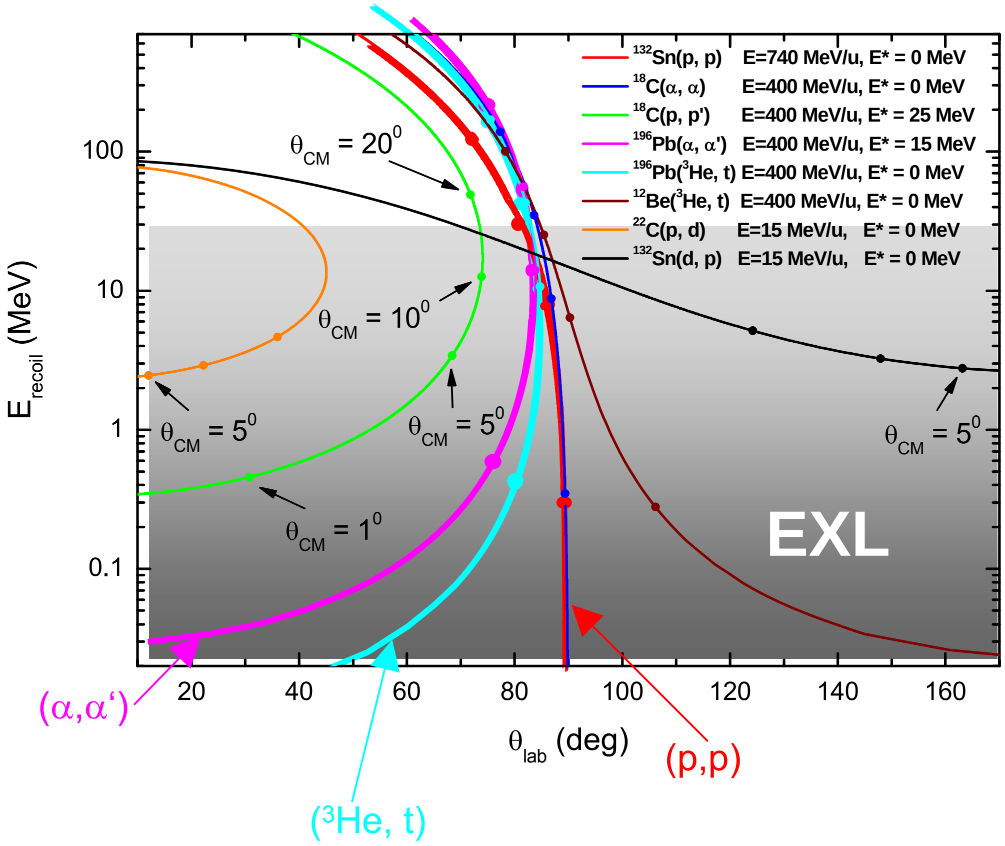
Inelastic alpha scattering on Sn isotopes (Giant Monopole Resonance)

Collective modes in asymmetric nuclei, nuclear matter compressibility



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

The EXL domain @ low-momentum transfer is essential for elastic & inelastic scattering and charge-exchange reactions



❖ Required beam energies

E ~ 200 – 740 MeV/nucleon (except for transfer reactions)

❖ Required targets

Light nuclei (e.g. ^{1,2}H, ^{3,4}He)

❖ Most important information in the region of low-momentum transfer

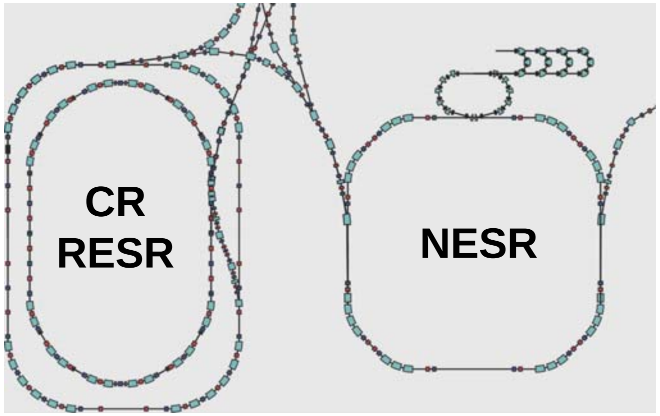
detect recoil particles of low energies

need thin targets for sufficient angular and energy resolution

Light-Ion Scattering with Radioactive Ion Beams

Rather limited applications to date…

The EXL experiment,
a huge leap forward:



- ➢ **Heavy-ion storage ring**
- ➢ **Internal gas/liquid jet target**

- **Inverse kinematics**
- **Measurements at low energy/momentum transfer**
  - → need very thin (windowless) target
  - → need to regain luminosity

from beam accumulation

from beam recirculation (NESR ~ 10^6 s^{-1})

- → need high resolution (recoil kinematics)

regain beam quality by electron cooling

Physics overlap with R^{3}B at the external target and with ELISe at the e-A collider

➔ **Complementarity**

Predicted Luminosities @ the NESR Storage Ring

Assumptions:

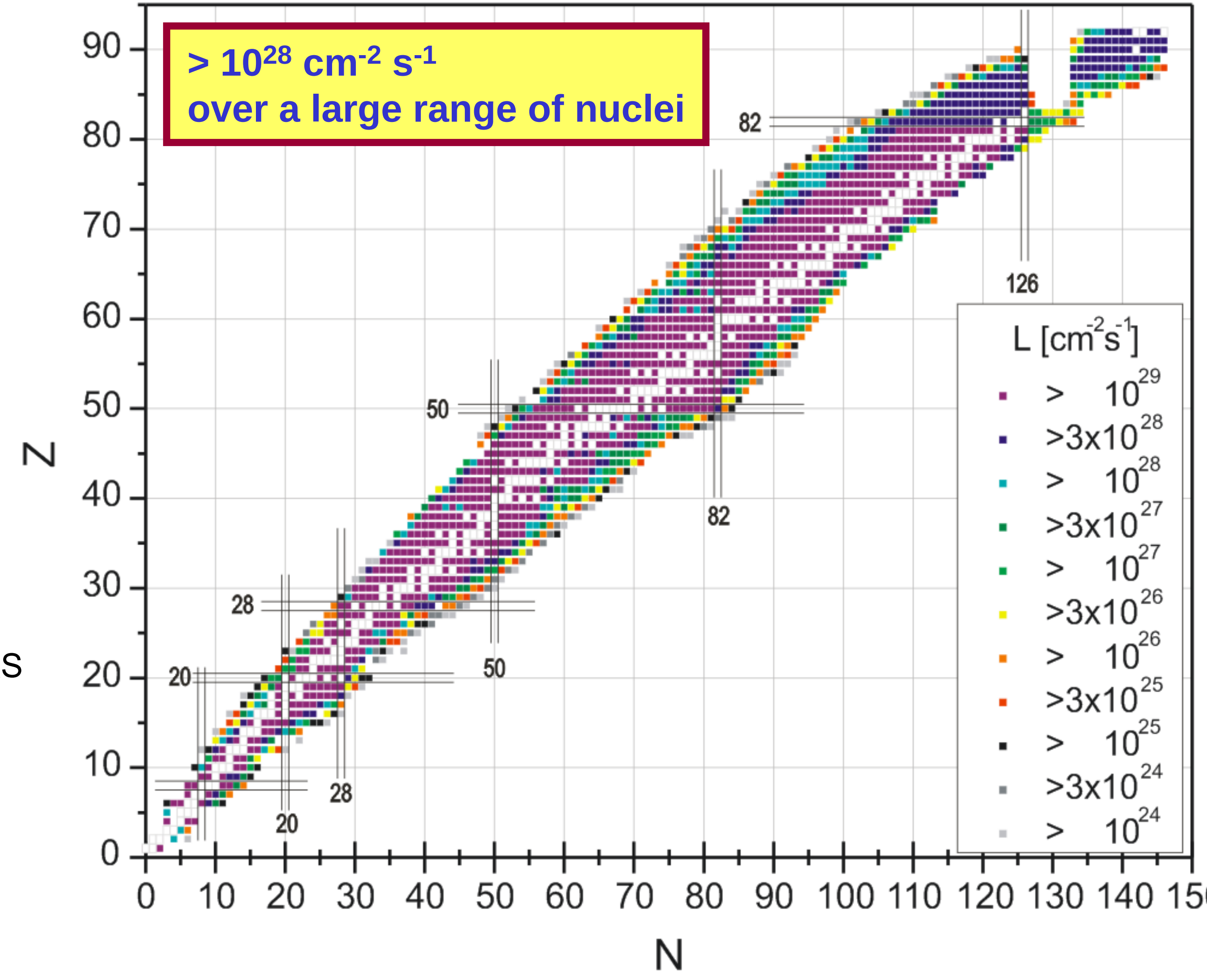
RIB @ 740 MeV/nucleon
(6×10^{11} ions/spill)

H gas-jet target
(10^{14} atoms/cm^2)

Cycle time 1.54 s

Including:

- Production rates
- Transmission through Super-FRS and into Collector Ring
- Losses due to nuclear decay (half-life) and electron capture in target or electron cooler

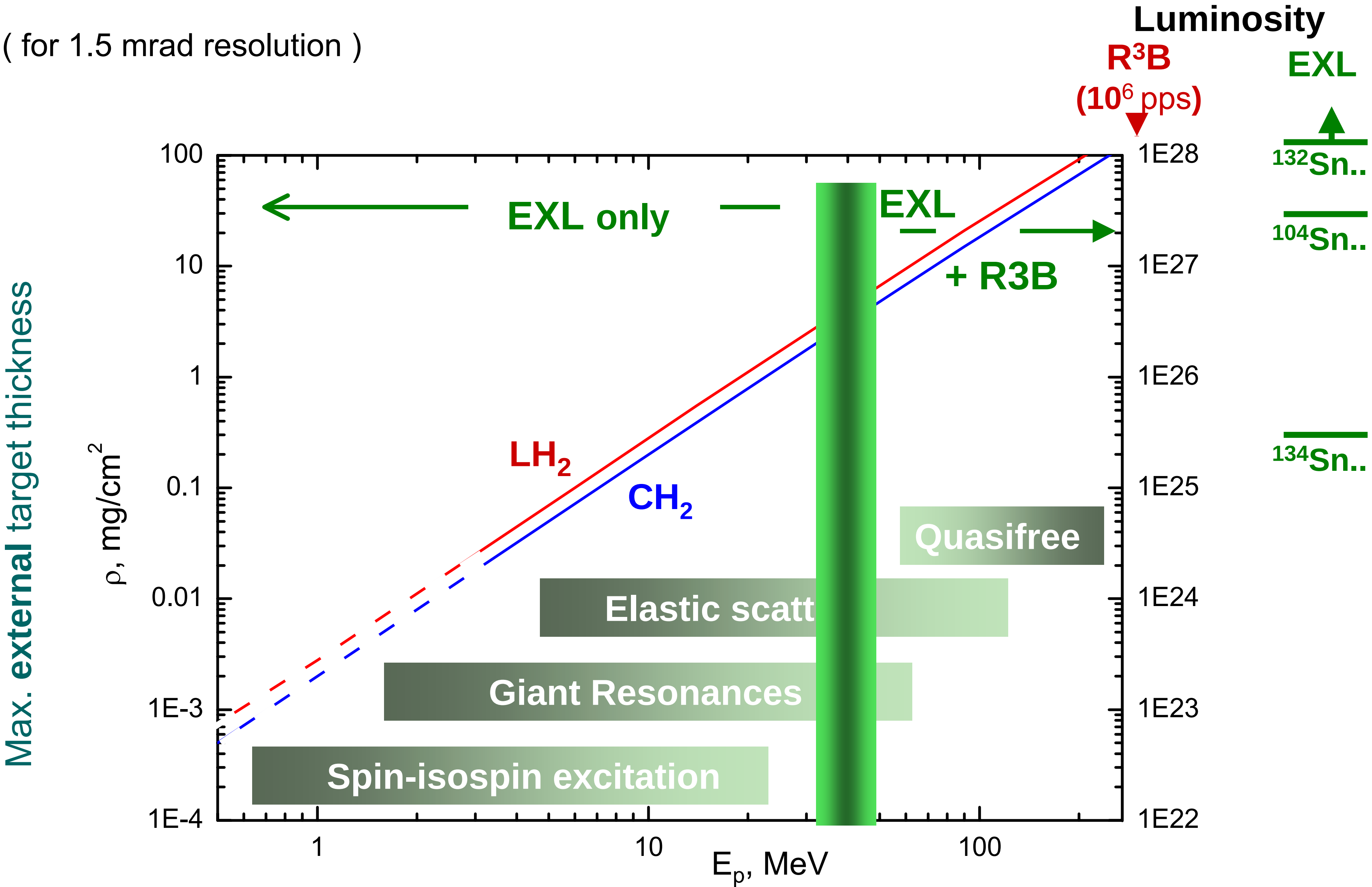


> 10^{28} cm^{-2} s^{-1}
over a large range of nuclei

Options to be explored: Deceleration, Multi-charge state operation *(increase luminosity)* ?

External Target versus Internal Target

(for 1.5 mrad resolution)



Advantages / Disadvantages of Storage Rings for Direct Reactions in Inverse Kinematics

- **Gain of luminosity**

Continuous beam accumulation and recirculation

- **High resolution**

Beam cooling, thin target

- **Low background**

Pure windowless ^{1,2}H, ^{3,4}He targets

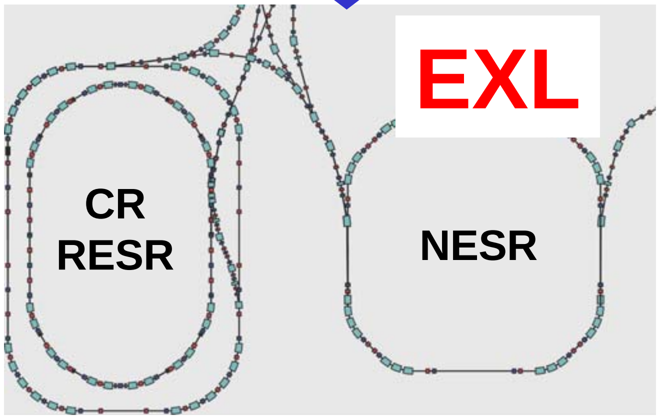
- **Separation of isomers**

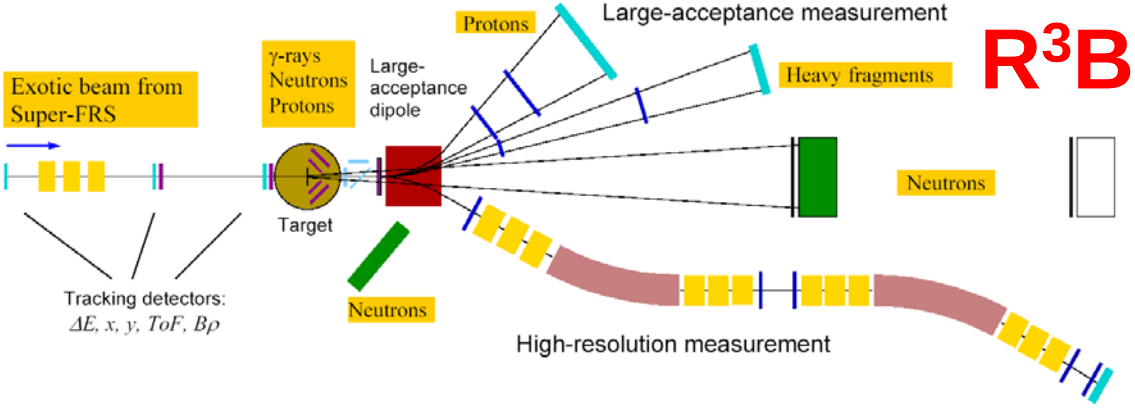
But:

Lifetime limit for very short-lived exotic nuclei (> 500 ms)

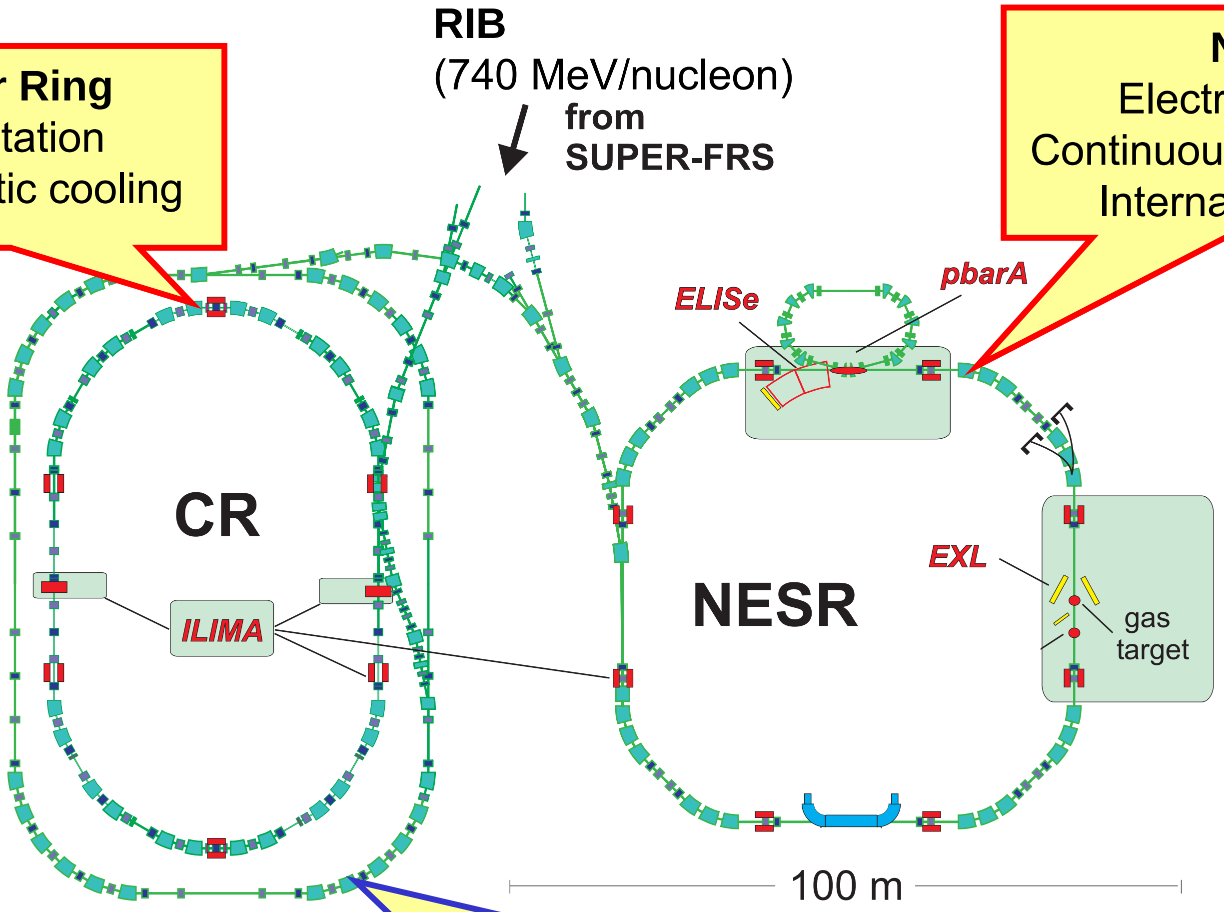
Active Target

(low rate capabilities ⇒ very exotic, short-lived nuclei)





NUSTAR Experiments with Stored Radioactive Beams @ FAIR

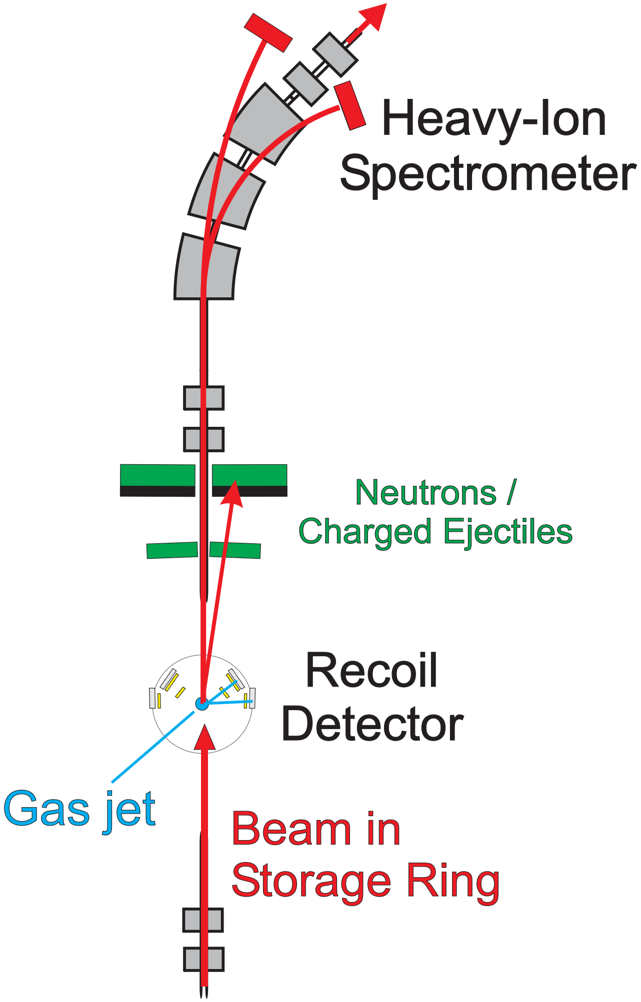


Collector Ring
Bunch rotation
Fast stochastic cooling

NESR
Electron cooling
Continuous accumulation
Internal jet targets

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

The EXL Experimental Set-up: Concept and Design Goals



Design goals

- Universality: applicable to a wide class of reactions
- High energy and angular resolution
- Fully exclusive kinematical measurements
- High luminosity (> 10^{28} cm^{-2} s^{-1})
- Large solid angle acceptance
- UHV compatibility (in part)

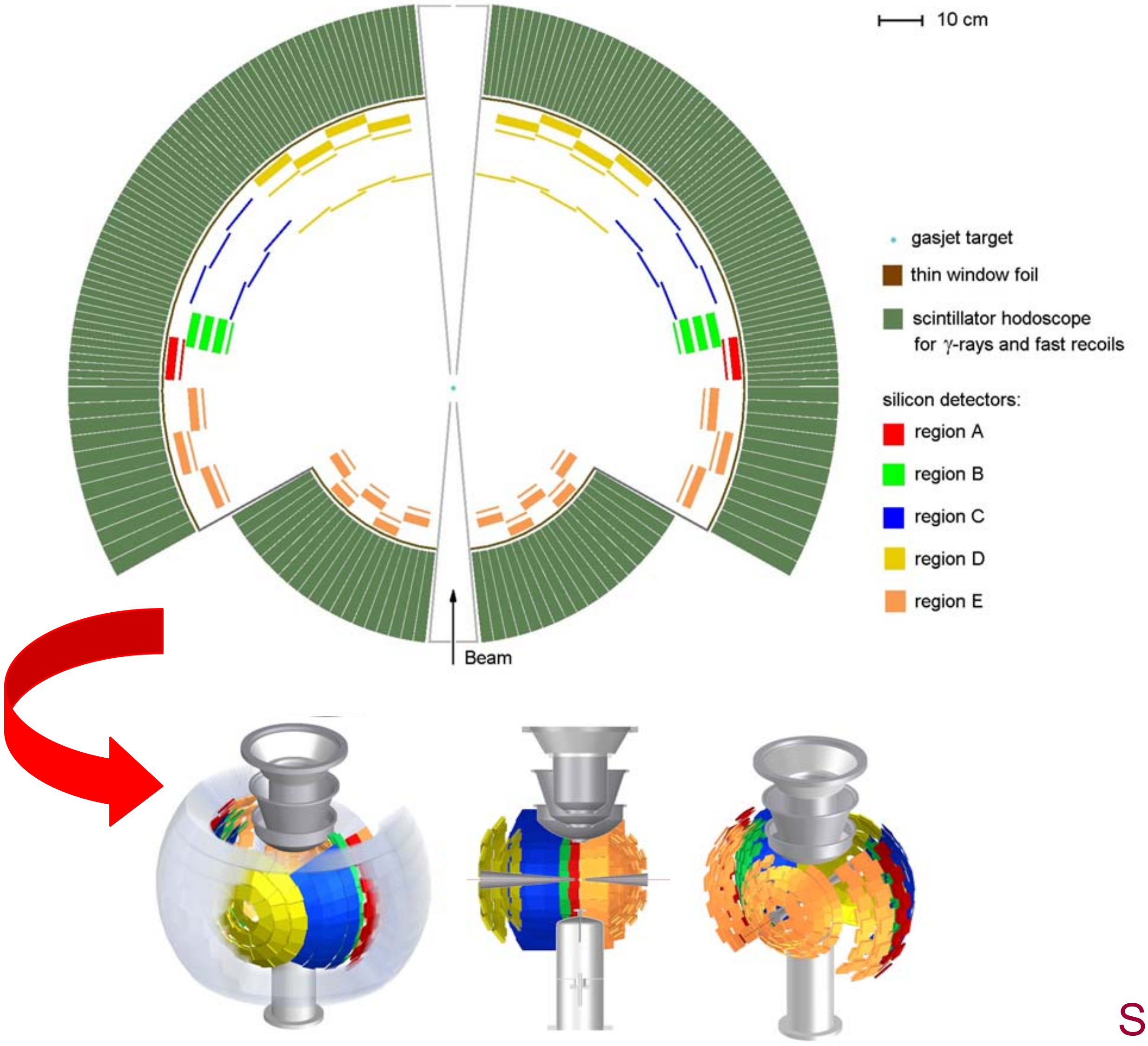
✓ Internal jet target (>10^{14} cm^{-2})

✓ Detection systems for:

  - Target recoils and gammas (p,α,n,γ…)
  - Forward ejectiles (p,n,γ)
  - Heavy fragments

Big R&D effort needed!

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)

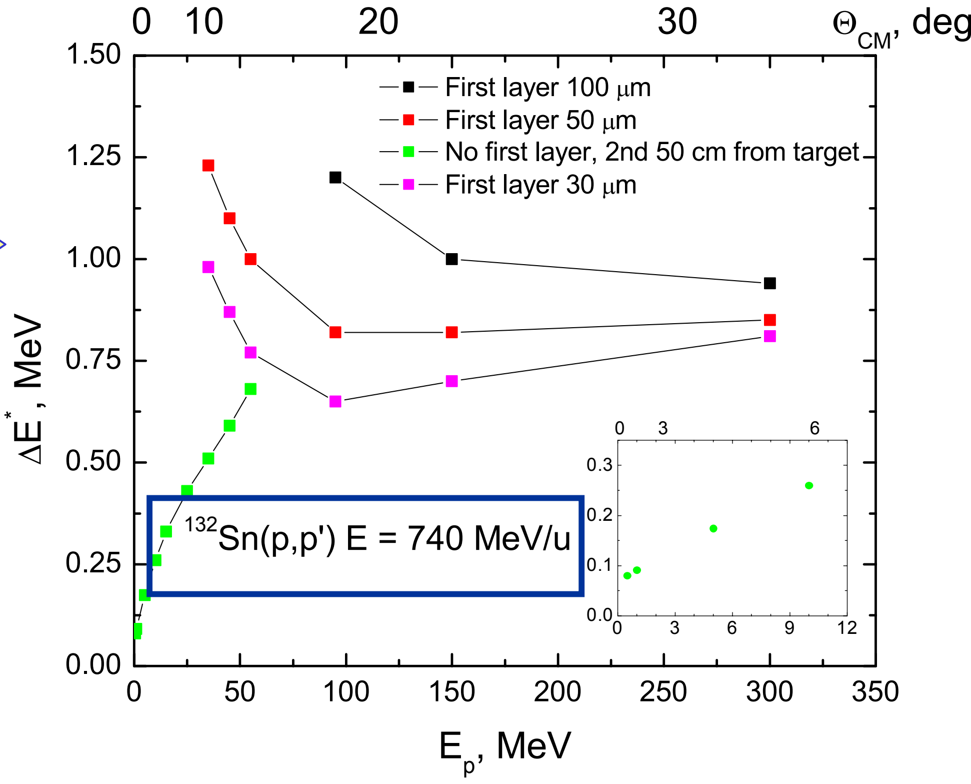
CsI crystals ⇨ E, γ
High efficiency, high resolution,
20 cm thick

Synergy with R^{3}B & NUSTAR.

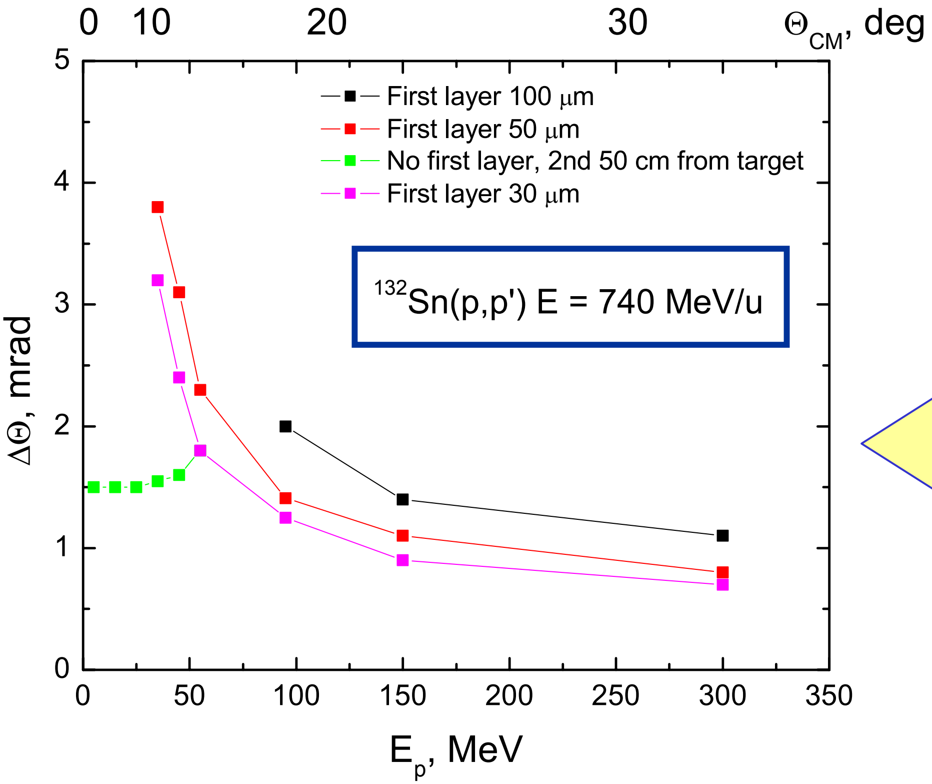
The EXL Recoil and Gamma Array

Simulations (Si array)

Energy resolution

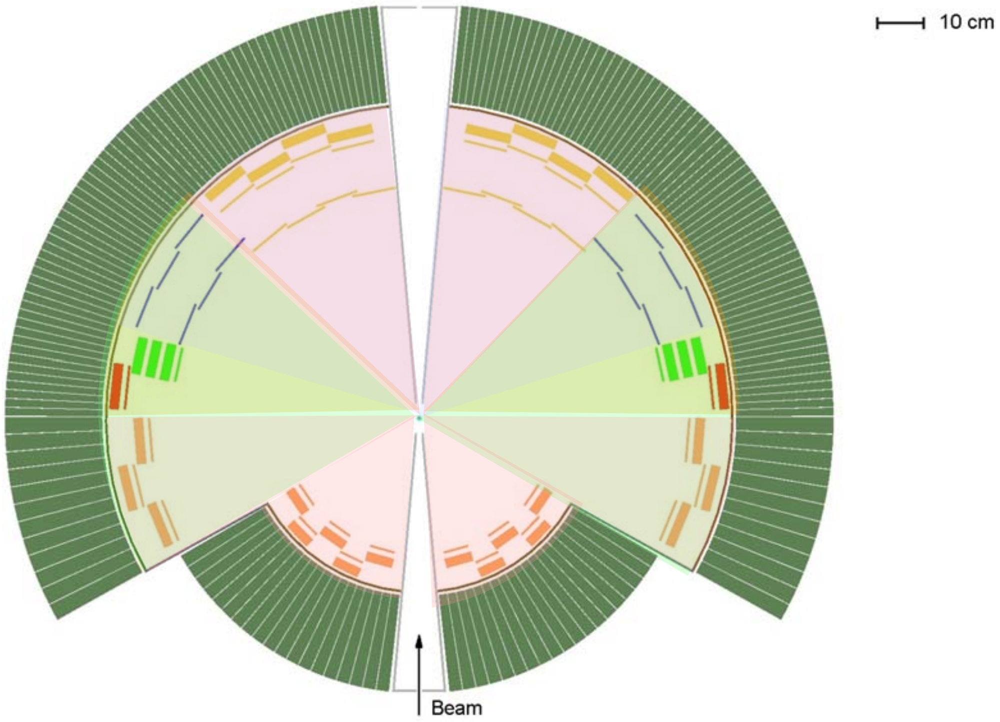


C.M. angle resolution



Design goals on resolutions are attainable.
But first silicon layer must be as thin as possible!

The EXL Recoil and Gamma Array



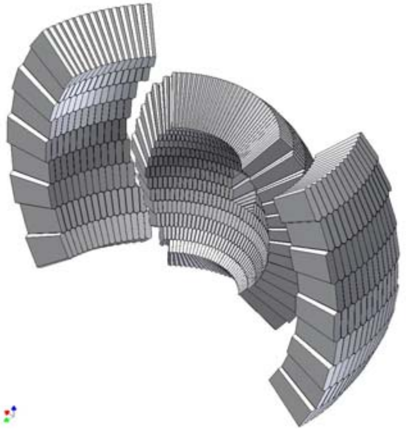
Calorimeter

**Forward angles (10° – 90°)
covered by 1304 single crystals
(2 different types)**

Angular resolution:
$\Delta \theta = 1.2°$
$\Delta \Phi = 8.8°$

**Backward angles (90° – 120°)
covered by 726 single crystals
(5 different types)**

Angular resolution:
$\Delta \theta = 2.3°$
$\Delta \Phi = 7.8°$



Modular Design

transfer reactions

Synergy with R^3B & NUSTAR.

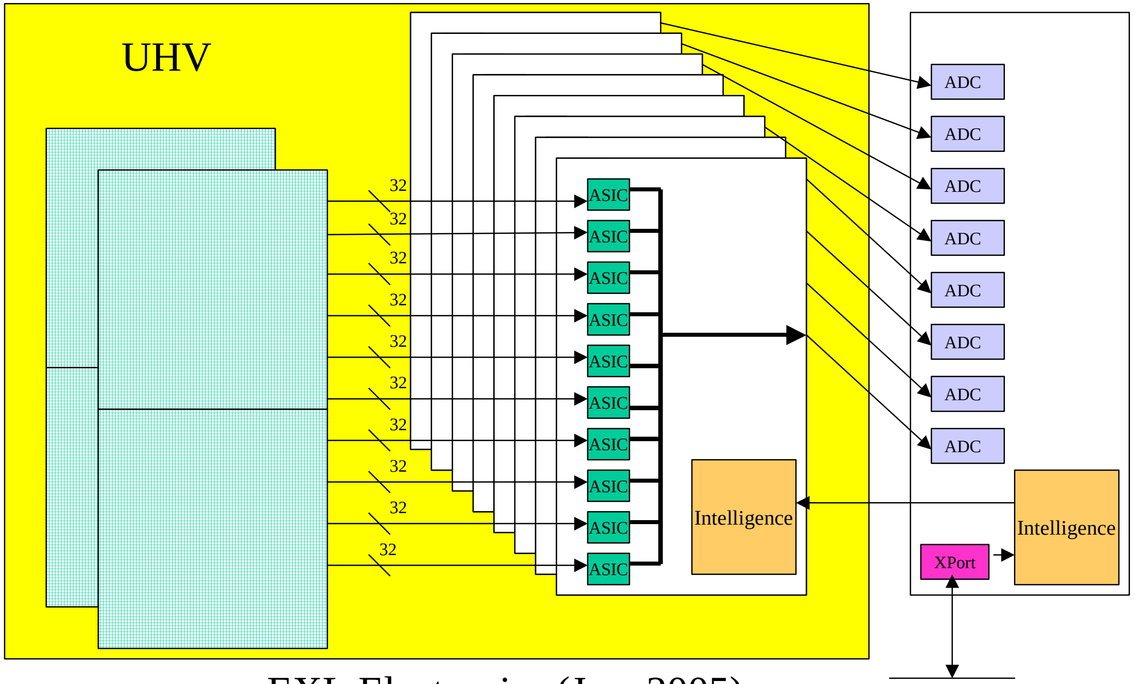
EXL Electronics R&D

- Large number of channels
- Large dynamic range, low thresholds
- UHV capabilities, baking, low power dissipation
- Space constraints

Detectors-
560000 channels
DSSD and SiLi

ASIC cards- approx
17500 ASICs on 1750 cards
(32 channels/ASIC)

ADC cards- 1750
ADCs on 219 cards
(320 channels/ADC)



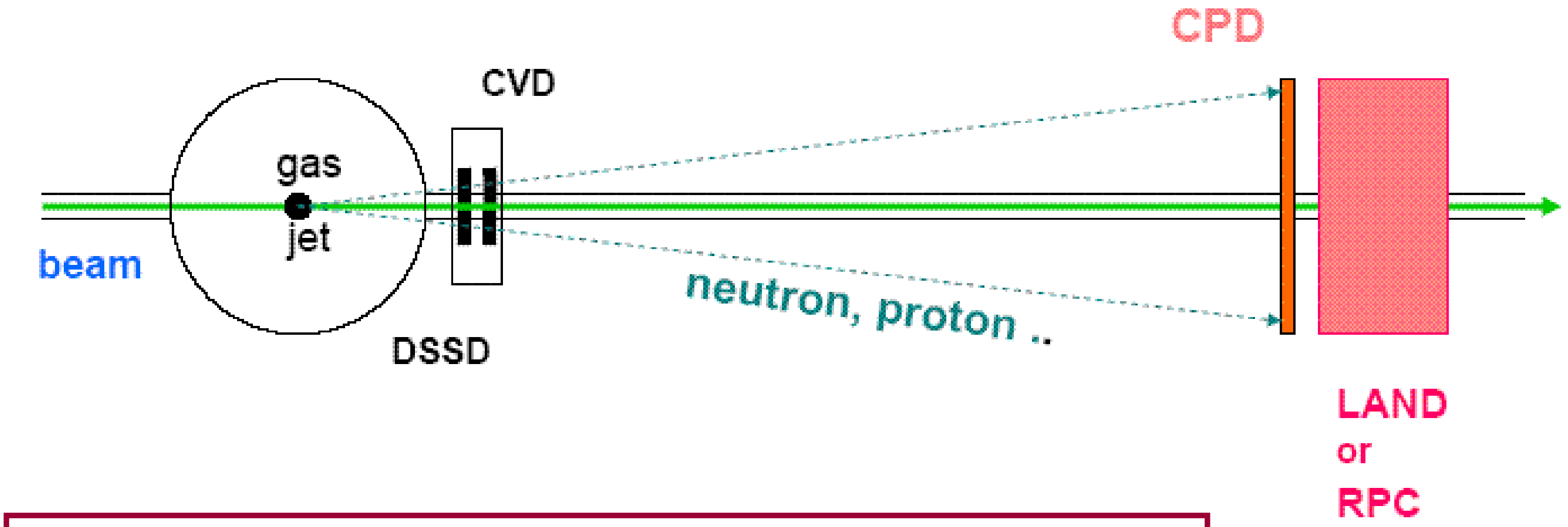
EXL Electronics (Jan 2005)

Synergy with NUSTAR.

The EXL Forward Ejectile Detector

Kinematically complete measurements:

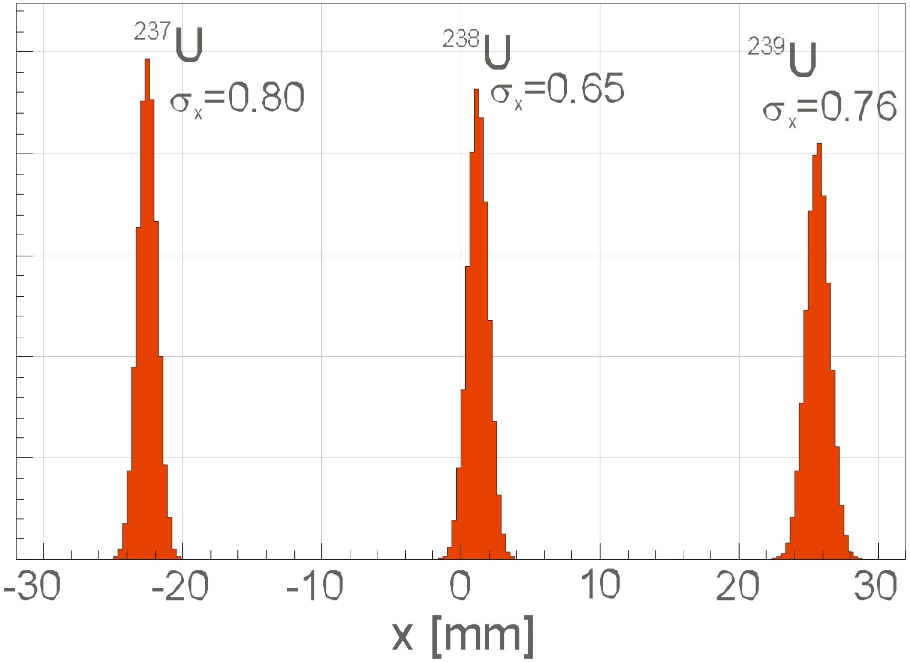
- detection of forward light particles emitted from the projectile (momenta measured)
- excitation energy of projectile residue, momentum (angular) correlations

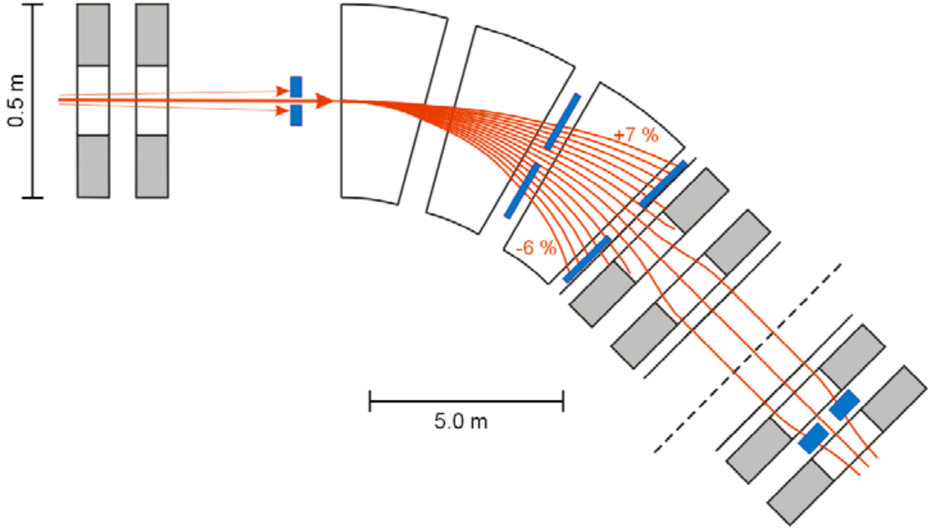


- High-resolution TOF and position measurements
- Full solid angle (forward focus)
- Calorimeter: scintillator + iron converter (similar to LAND)

Synergy with R^{3}B.

The EXL In-Ring Heavy-Ion Spectrometer





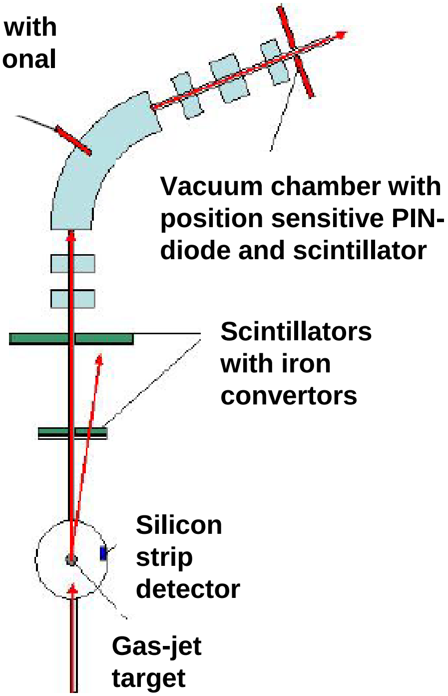
- ❖ **Ion-optical mode for NESR as fragment spectrometer**
- ❖ **3 heavy-ion detector stations:**
- <u>in front of first dipole magnet for 'reaction tagging‘ (main mode)</u>
- inserted into dipole section for 'tracking' of fragments
- inserted into quadrupole section for 'imaging' properties of magnetic spectrometer (limited acceptance)

Synergy with ELISe and AIC.

Test Experiments at the ESR

350 MeV/nucleon ^{136}Xe beam
H_2 gas-jet target
Luminosity 10^{27} $s^{-1}cm^{-2}$

ESR
Storage
Ring



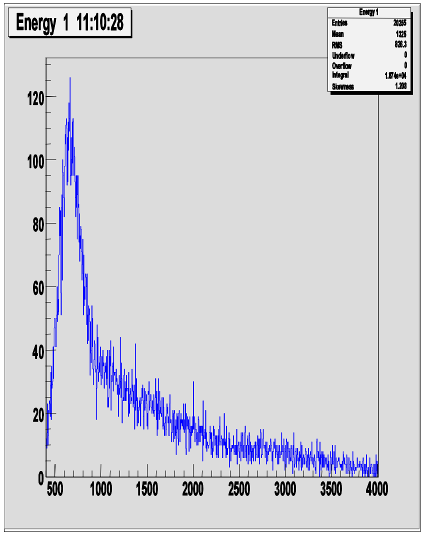
Vacuum chamber with multiwire proportional chamber

Vacuum chamber with position sensitive PIN-diode and scintillator

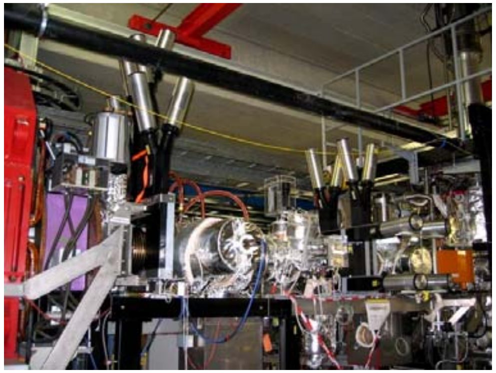
Scintillators with iron convertors

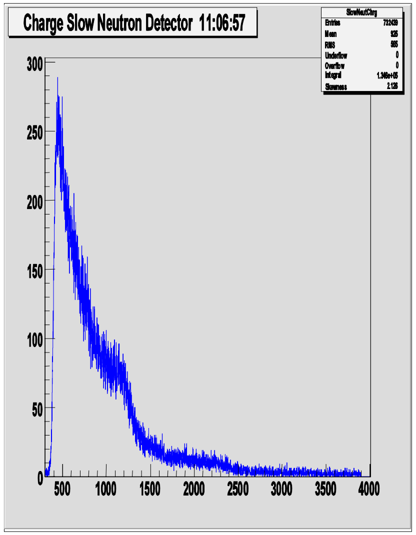
Silicon strip detector

Gas-jet target

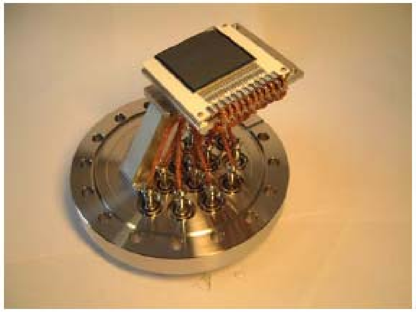


Scintillator array for the detection of fast ejectiles





UHV capable Si-strip detector for recoil protons



- Active area: 40×40 mm^2
- Thickness: 1 mm
- 40 Strips (Pitch: 1 mm) connected for read-out in groups of 8, each one with two output pins
- Energy resolution 35 ± 5 keV for α-particles with E = 5.5 MeV

Some Exciting Challenges Today...

Recoil detector:

- High resolution: $\Delta E \sim 50$ keV, $\Delta\vartheta \sim 1$ mrad
- Low thresholds
- UHV compatible (in part)

Target:

- Cluster jet density and extension (≤ 1 mm)
- Alternative targets (pellet; fibre; He superfluid jet; polarized) ?

Ion-optical mode for NESR as fragment spectrometer

Options to be explored:

- Deceleration down to ~ 15 A.MeV ?
- Multi-charge state operation ?

For Some Exciting Physics Tomorrow!

The EXL Collaboration

Spokesperson: M. Chartier (Liverpool)
Deputy: P. Egelhof (GSI)
15 countries, 32 institutes, ~ 130 participants

Univ. São Paulo

TRIUMF Vancouver

IPN Orsay

GSI Darmstadt, TU Darmstadt, Univ. Frankfurt, FZ Jülich, Univ. Mainz, Univ. Munich

INR Debrecen

SINP Kolkata, BARC Mumbai

Univ. Tehran

INFN/Univ. Milano

Univ. Osaka

KVI Groningen

JINR Dubna, NPI/KRI/Univ. St Petersburg, KI Moscow

CSIC Madrid, Univ. Madrid

Göteborg, Univ. Lund, Mid Sweden Univ., TSL Uppsala

Univ. Basel

Univ. Birmingham, CLRC Daresbury, Univ. Liverpool, Univ. Surrey