# Exotic Nuclei and Radioactive Beams at High Energy

T. Aumann

***Gesellschaft für Schwerionenforschung***

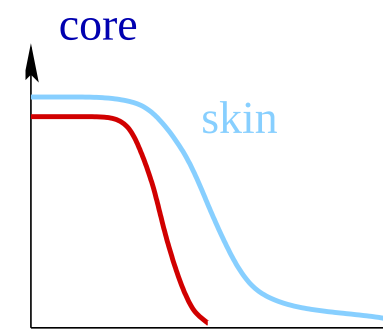
EPS-12: Trends in Physics, Budapest, 29th August 2002

- ★ Introduction / Experimental concept
- ★ Results: two examples
  - ➤ knockout reactions with halo nuclei
  - ➤ electromagnetic scattering of n-rich nuclei
- ★ Future developments

# Reactions with Light Neutron-Rich Nuclei

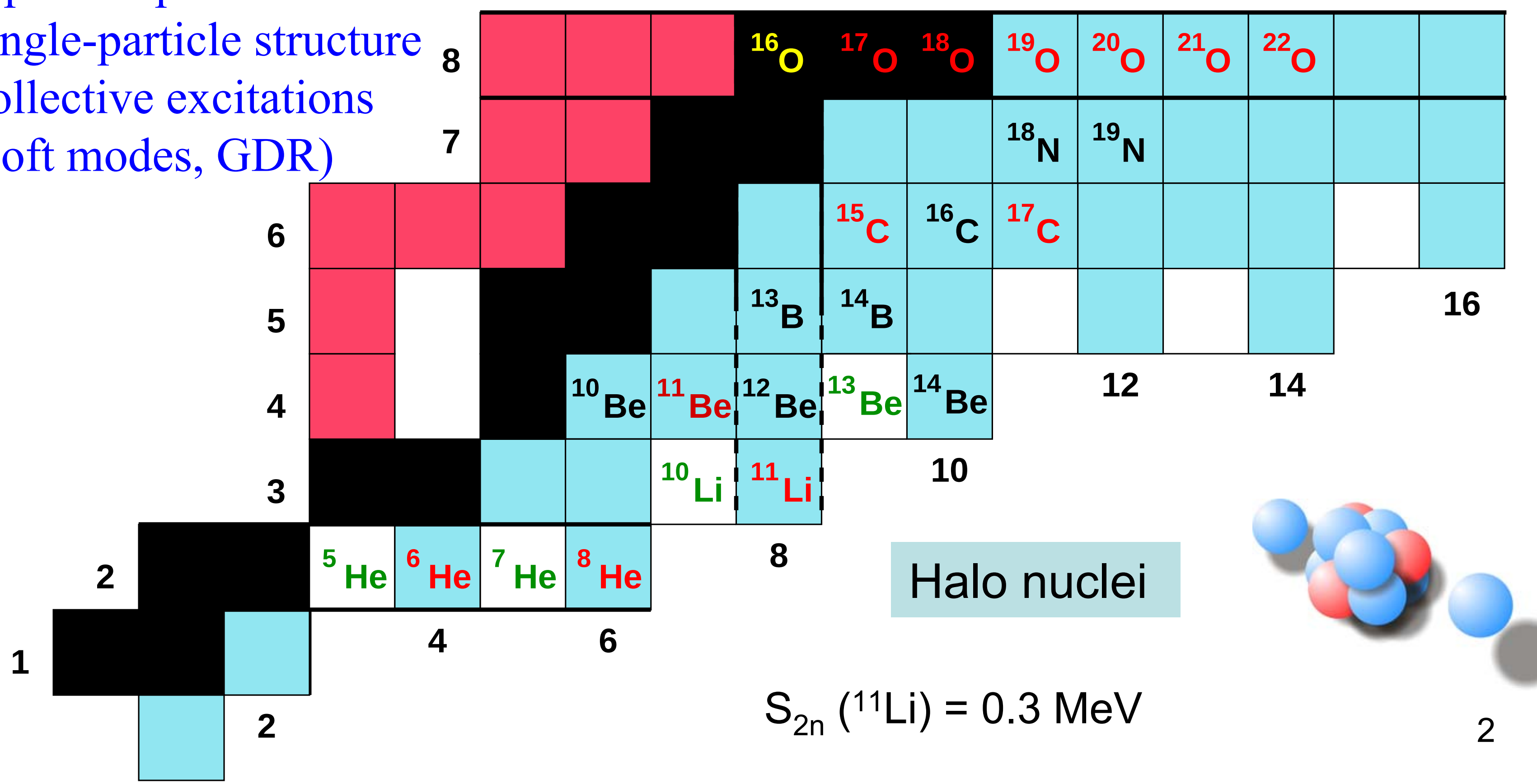
- ♦ **Knockout**
  - ➤ single-particle structure
  - ➤ unbound states
- ♦ **Electromagnetic excitation**
  - ➤ dipole response
  - ➤ single-particle structure
  - ➤ collective excitations (soft modes, GDR)

Neutron skin




$S_n \sim 16$ MeV

$S_n \sim 4\text{-}7$ MeV




Halo nuclei

$S_{2n}$ ($^{11}$Li) = 0.3 MeV

# Scattering Experiments with High-Energy Secondary Beams

**0.6 < v/c < 0.8**

## Physics Aspects:

**p/A** ~ 1 GeV/c **>** $p_{Fermi}$ ==> sudden process

**short** interaction time ==> high Fourier components

$\sigma_{NN}$ lowest at ~ 400 MeV ==> reduced re-scattering

low transverse momentum ==> Eikonal approximation

transverse Coulomb field (essentially dipole excitations)

## Experimental Aspects:

Thick targets (~g/cm$^2$) ==> increased luminosity

4π solid angle coverage (projectile rapidity)

100% detection efficiency (even for neutrons)

***--- compensating low beam intensity***

***( 1 - 10000 s$^{-1}$ ) ---***

**GSI:** up to 1 GeV/u

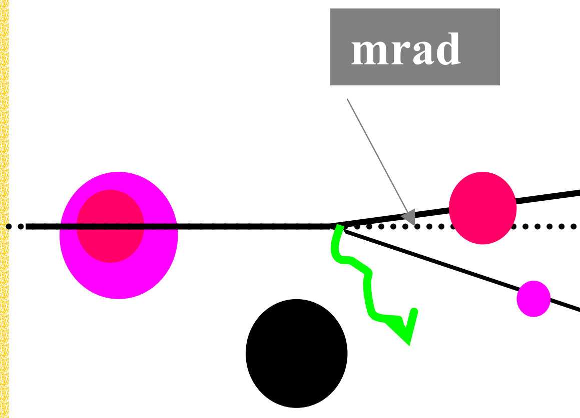
**Other Laboratories**

(up to ~ 100 MeV/u):

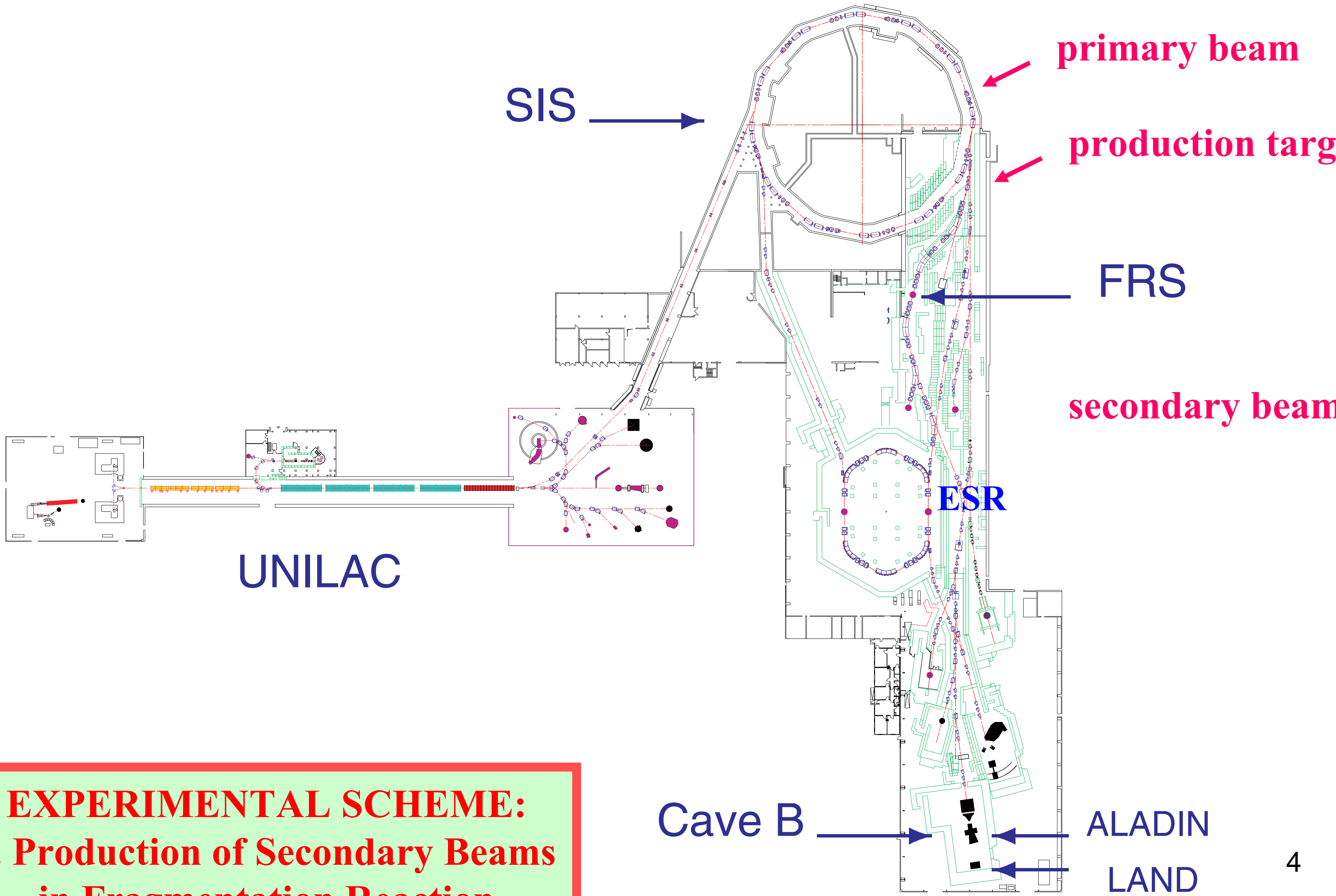
**GANIL / France**

**MSU / U.S.**

**RIKEN / Japan**



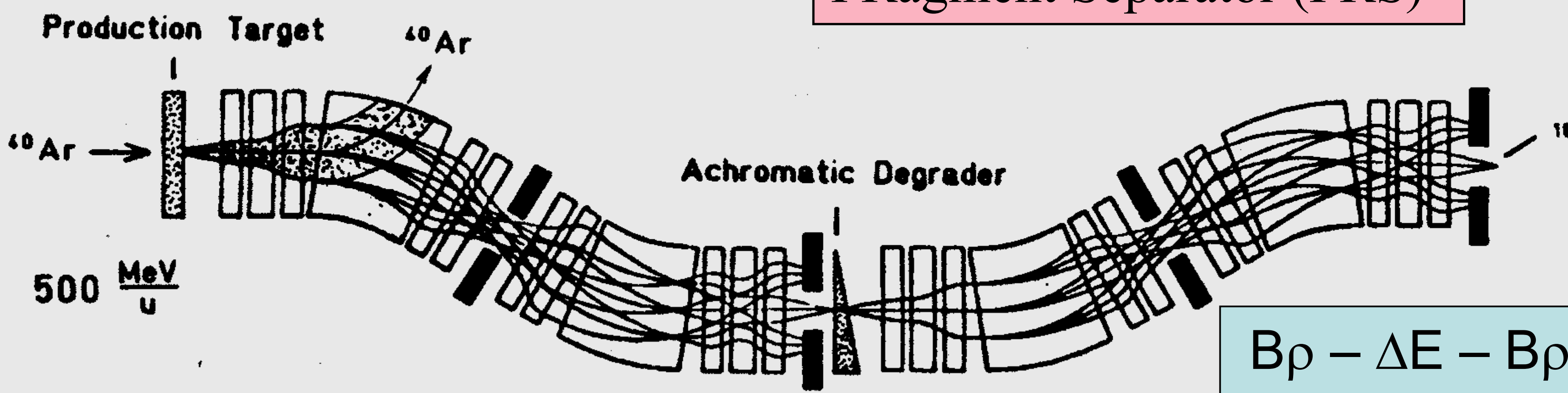
# The GSI Accelerator Facilities




**EXPERIMENTAL SCHEME:**
**I. Production of Secondary Beams in Fragmentation Reaction**

# Experimental Scheme:
# II. Separation in FLIGHT

FRagment Separator (FRS)




$B\rho - \Delta E - B\rho$
Method

$B\rho \propto \beta\gamma\, A/Z$
$\Delta E \propto Z^2 f(\beta)$

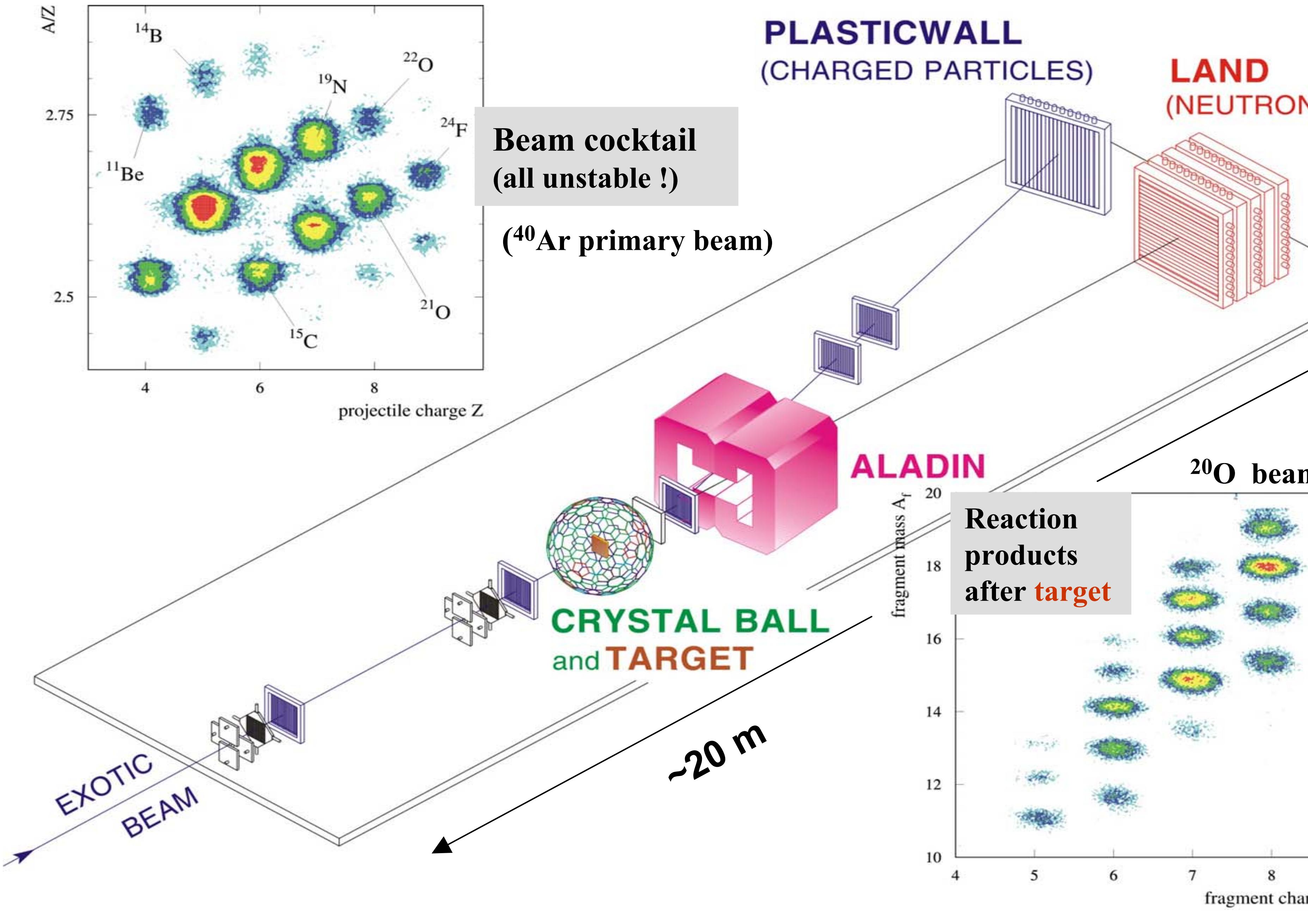
**Separation in Flight : $v_{Frag.} = v_{Beam}$**

**Transport efficiency ~ 50 % ; $\Delta p/p$ ~ 2 %**

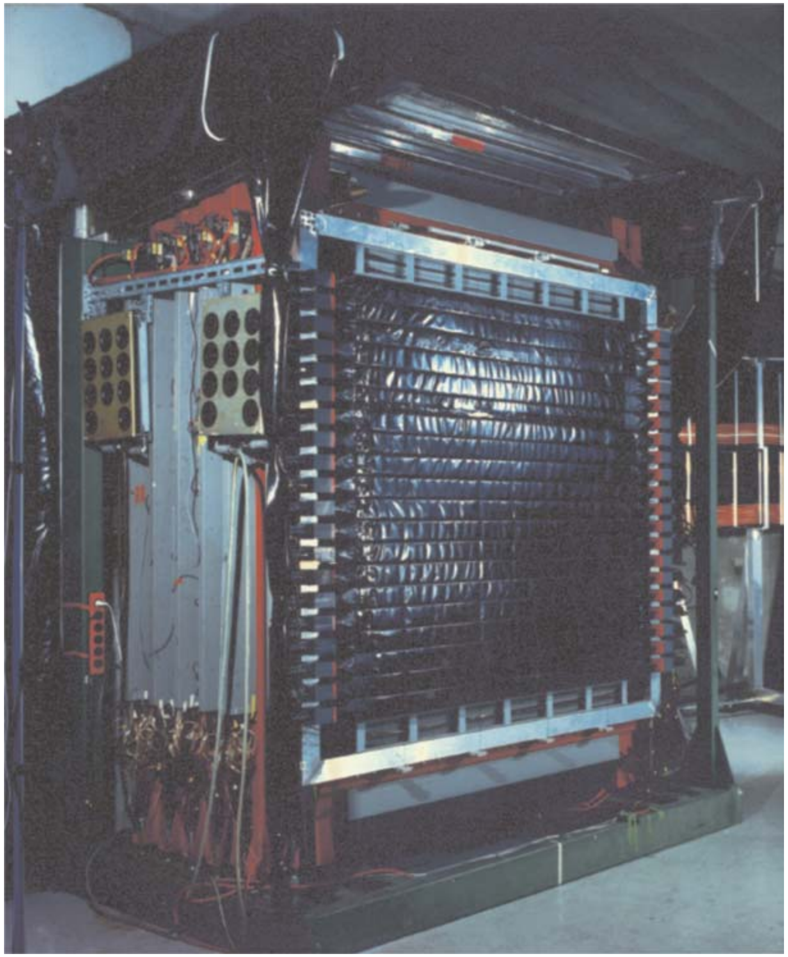
**Magnetic separation only: <u>mixed beam</u> (Z/A ~ const.)**

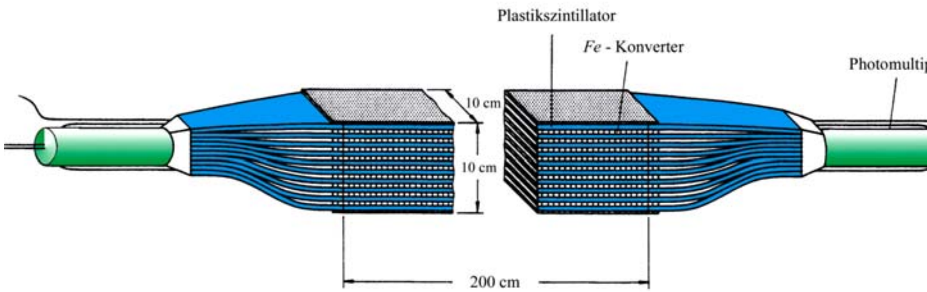
H. Geissel et al., NIM B 70 (1992) 286

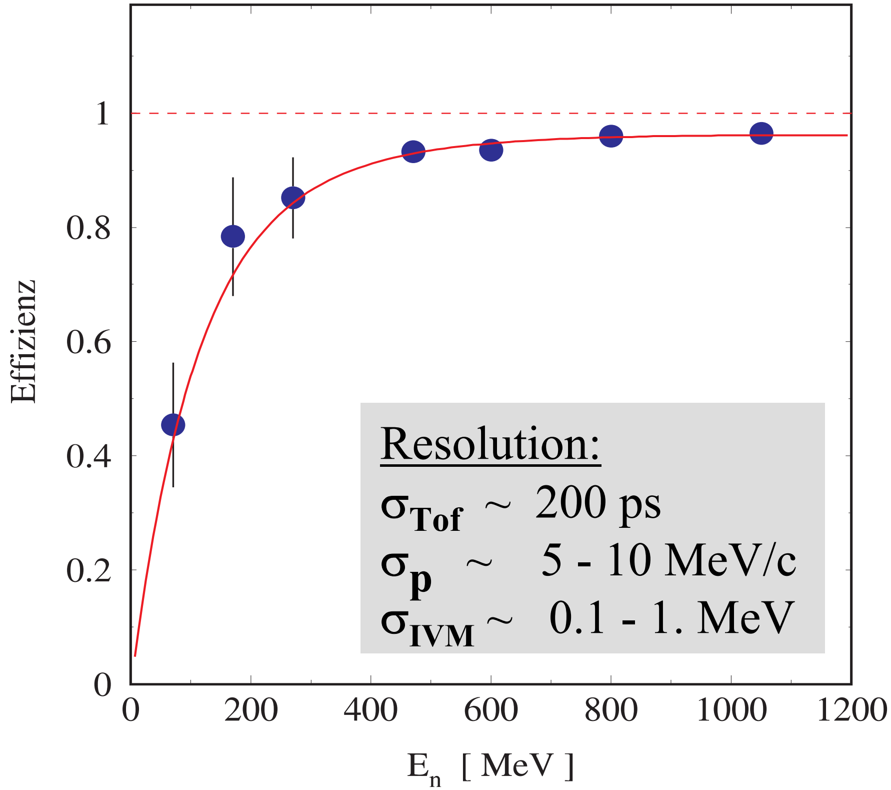
# Experimental Scheme: III. Setup LAND@GSI



# The Large Area Neutron Detector LAND








**Nucl. Instr. Meth. A314 (1992) 136**

# Experimental Observables

**Measured:**

- **Momenta of projectile reaction products**
  **(fragment, neutrons, charged particles )**
- **γ-rays**

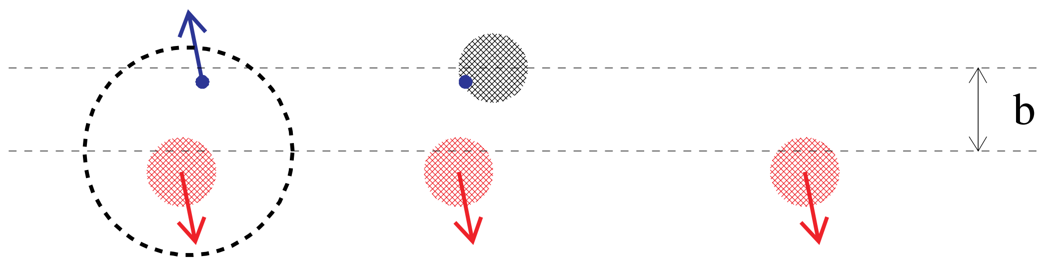
**Deduced Observables:**

**==> momentum and energy transfer**
**==> projectile excitation energy (invariant mass)**
**==> fragment excited states after breakup (γ-rays)**
**==> momentum / angular correlations**
**==> (differential) cross sections ( if > ~ 10 - 100 mbarn )**

**Typical Reactions:**

- **(in-) elastic scattering**
- **quasi-free scattering (knockout)**
- **Coulomb breakup on *high-Z* target (*Pb..)***

# One-Nucleon Knockout: a Spectroscopic Tool




Sudden process

Reaction: $\Delta t \approx 10^{-22}$ s

Internal motion: $\approx 10^{-21}$ s

$\Rightarrow$ **$P_{frag} = -P_n$**

$\Rightarrow$ **measurement of wave function (at the surface: $b_c > r_c$)**

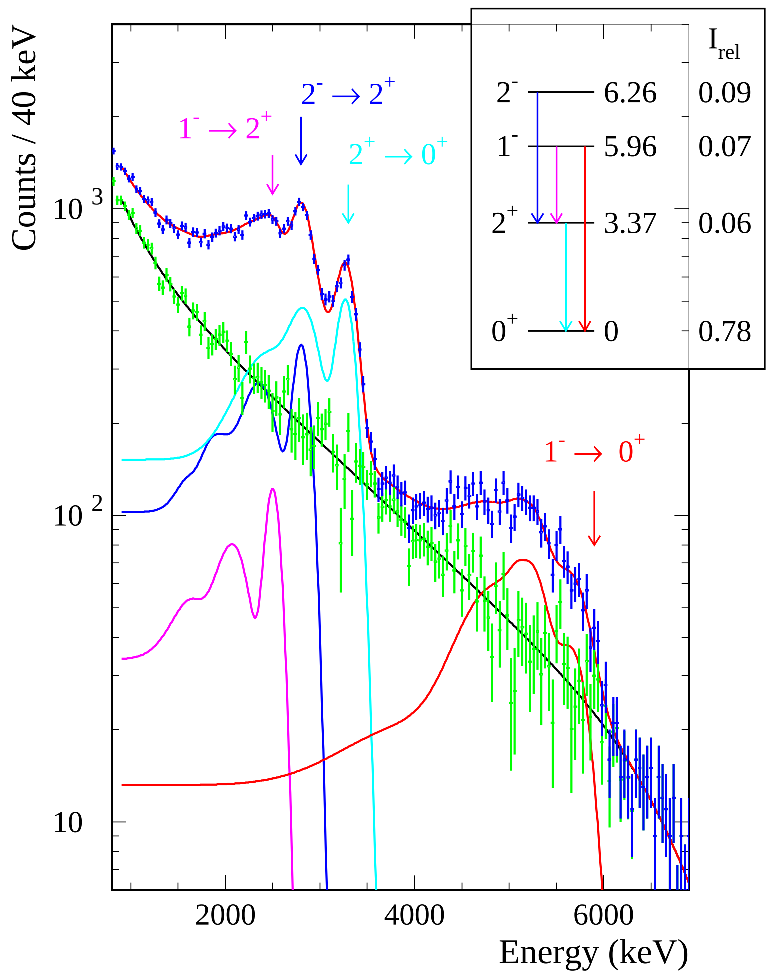
| Measurement | Observable |
|---|---|
| Momentum distribution | $\Rightarrow$ *l*-value of removed nucleon |
| $\gamma$-ray coincidence | $\Rightarrow$ identification of core-state |
| invariant mass (unbound states) | |
| Cross section | $\Rightarrow$ spectroscopic factor |

$$\sigma_{1n}(J^\pi) = S(J^\pi) \times \sigma_{sp}(l, S_n)$$

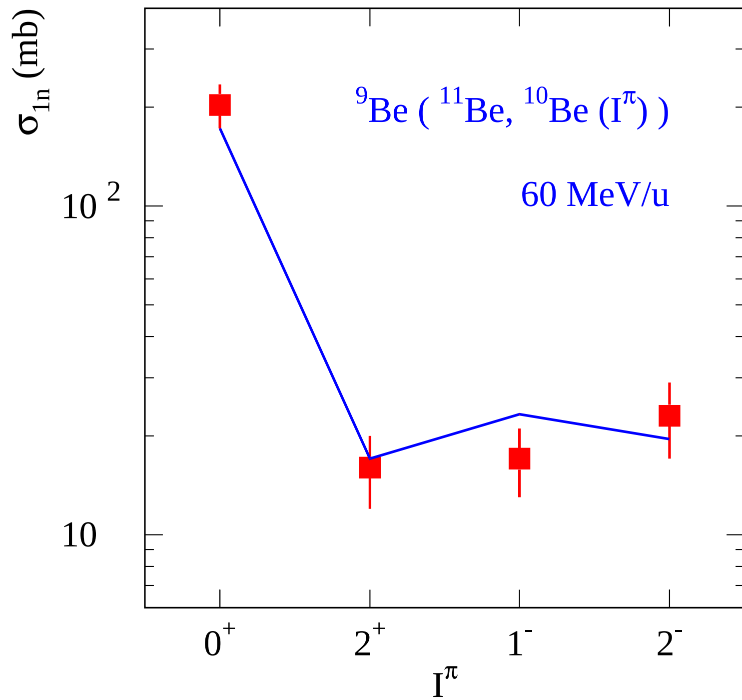
Eikonal calculation

# Neutron removal from individual single-particle states: $^{11}Be \rightarrow {}^{10}Be\,(I^{\pi}) + \gamma + X$

γ-ray coincidences




Partial cross sections




Spectroscopic factors



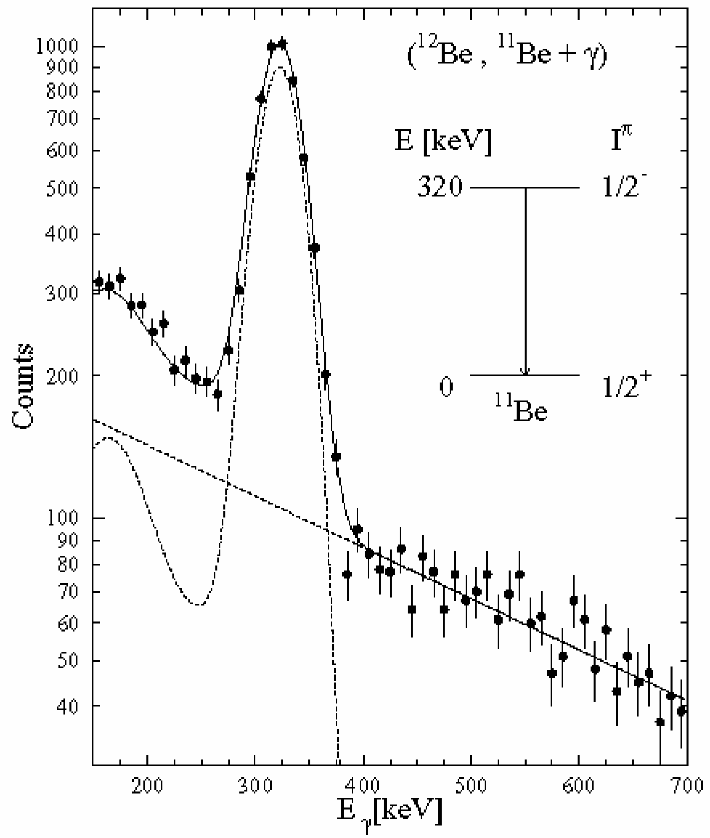
Data: S800@MSU, T.Aumann *et al.*, PRL 84 (2000) 35

# $^{12}$Be: Breakdown of the N=8 Shell Closure

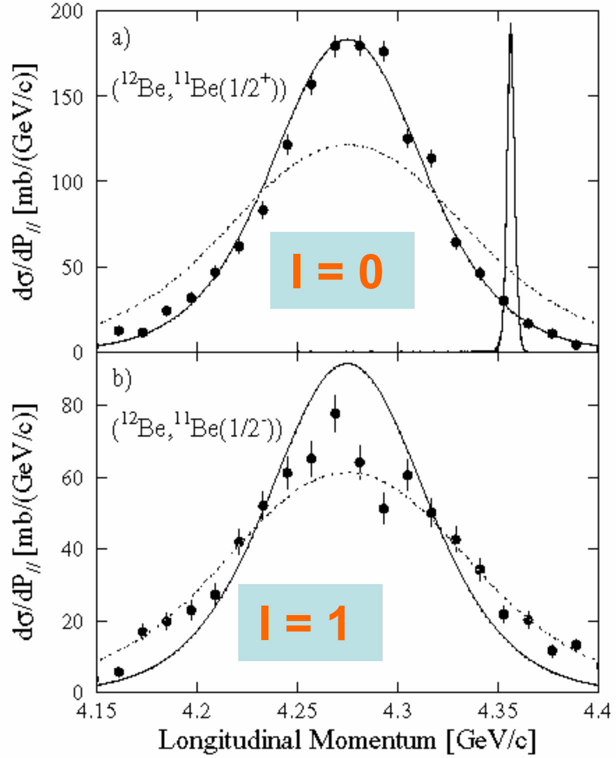
One-neutron removal reaction:

$^{12}$Be (@78 Mev/u) + $^{9}$Be → $^{11}$Be($I^{\pi}$) + γ + X

γ-ray coincidences




Momentum distributions




**⇒ Mixed configurations**

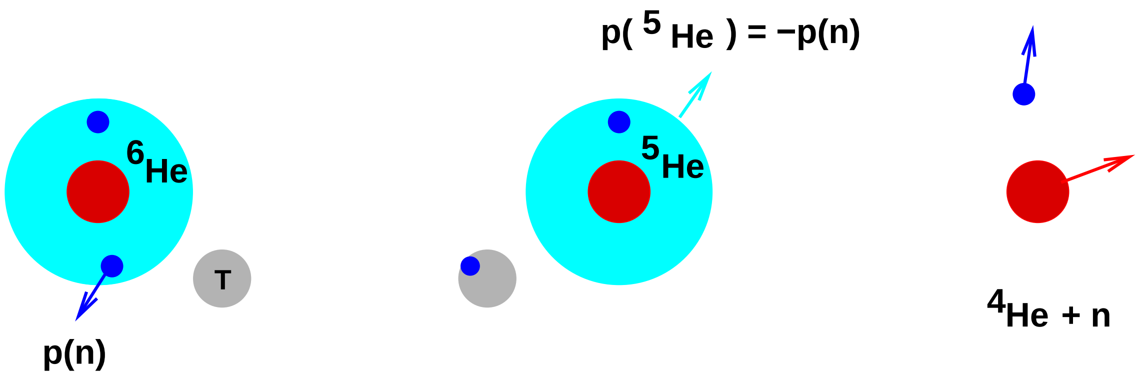
**$(\nu s_{1/2})^2 / (\nu p_{1/2})^2 \approx 1$**

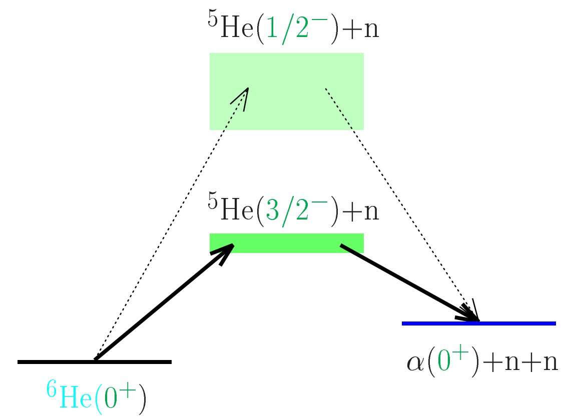
Data: S800@MSU, A. Navin *et al.*, PRL 85 (2000) 266



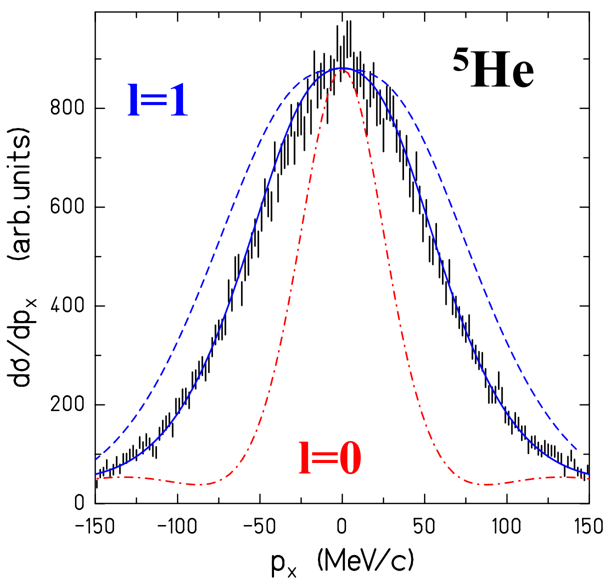
See $^{11}$Li, talk of Haik Simo

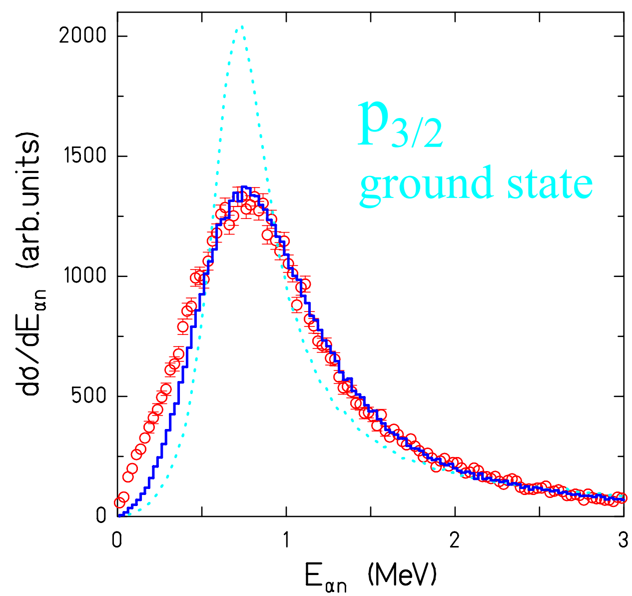
# Knockout to Continuum States

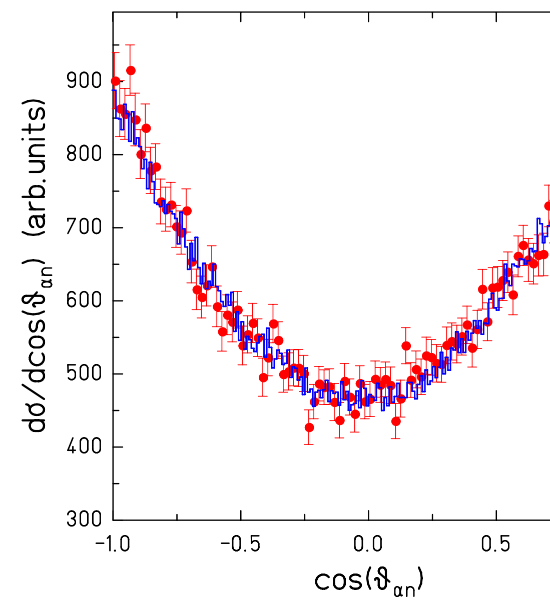



**Momentum distribution** | **Relative energy $^4$He↔n** | **Angular correlation**




Data: LAND-FRS@GSI, D. Aleksandrov et al., NPA 633 (1998), L. Chulkov et al., PRL 79 (1999) 201



Structure of 2n-halo nuclei, spectroscopy of unbound states, see talk by Haik Simon

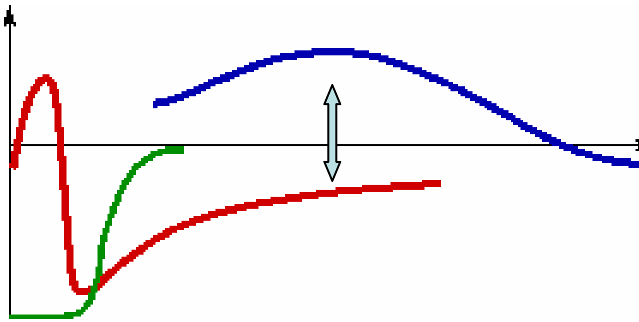
# Dipole Response of Exotic Nuclei

? Strong fragmentation of strength

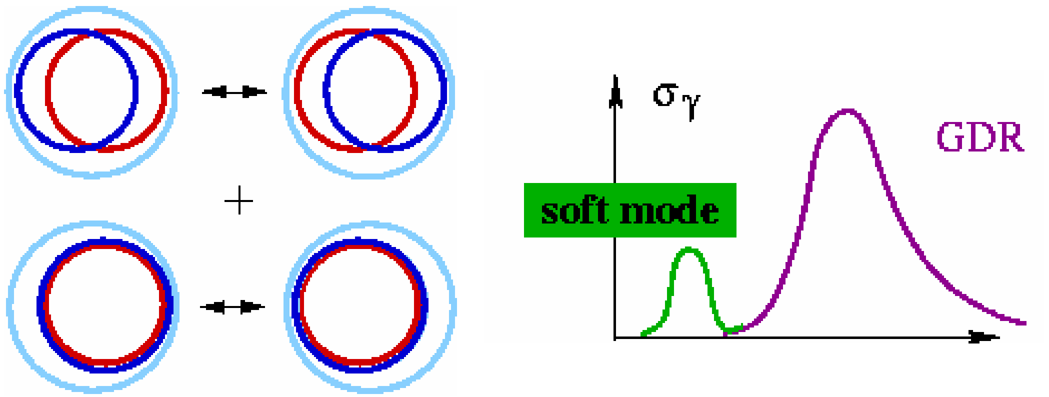
Appearance of low-lying strength

! ‘Threshold’ strength (low-lying, non-resonant ($\gamma$,$n$) strength)

? New coherent ‘soft’ excitation modes



Strong non-resonant transition




- Effective forces

  dependence on isospi

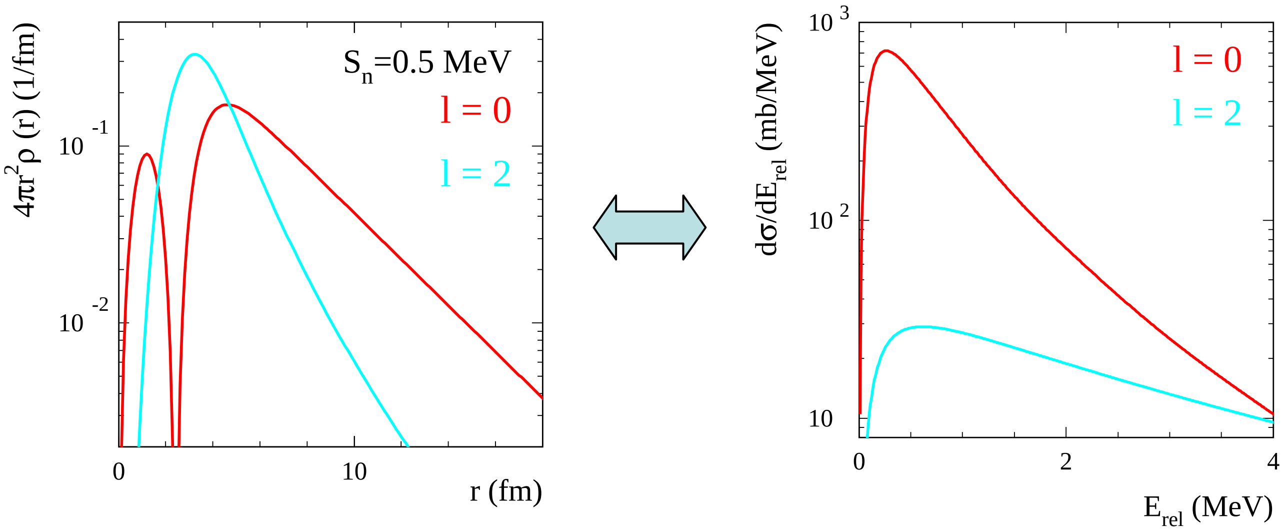
- Single-particle structure
- Astrophysical implications

# Low-Lying E1 Strength of Weakly Bound Nuclei

Wave function: e.g. $|^{11}\mathrm{Be}\rangle = \alpha|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle + \beta|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + \ldots$

$$d\sigma/dE_{rel} = \frac{16\pi^3}{9\hbar c} N_{E1}(E^*) \; |\langle q | \frac{Ze}{A} r Y^1_m | \Phi_v(r) \rangle|^2$$

Density distribution — Differential cross section




Spatial extension (Halo)

⇒ Strong non-resonant transitions

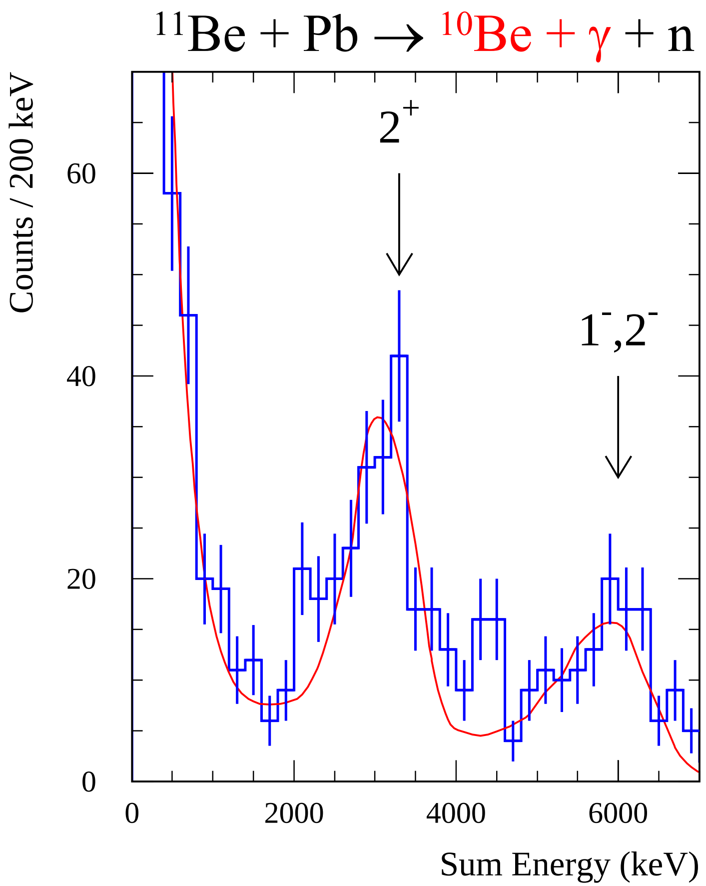
**Shape of differential cross section ⇒ angular momentum *l***

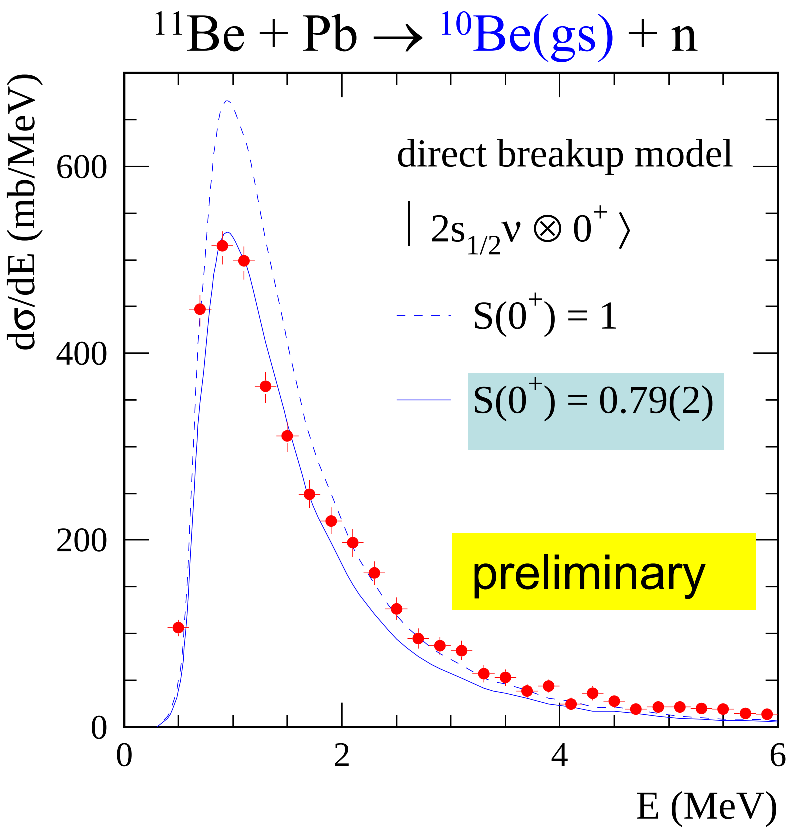
**γ-ray coincidence ⇒ identification of core state**

**Cross section ⇒ spectroscopic factor**

# Coulomb Breakup of $^{11}$Be: The Classical One-Neutron Halo

$$|^{11}\mathrm{Be}\rangle = \sqrt{S(2^+)}\,|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + \sqrt{S(0+)}\,|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle + \ldots$$



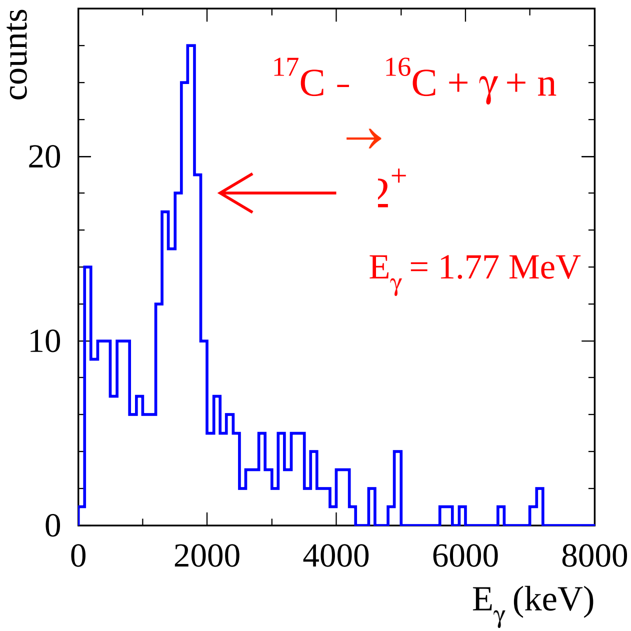

**Consistent experimental results**:

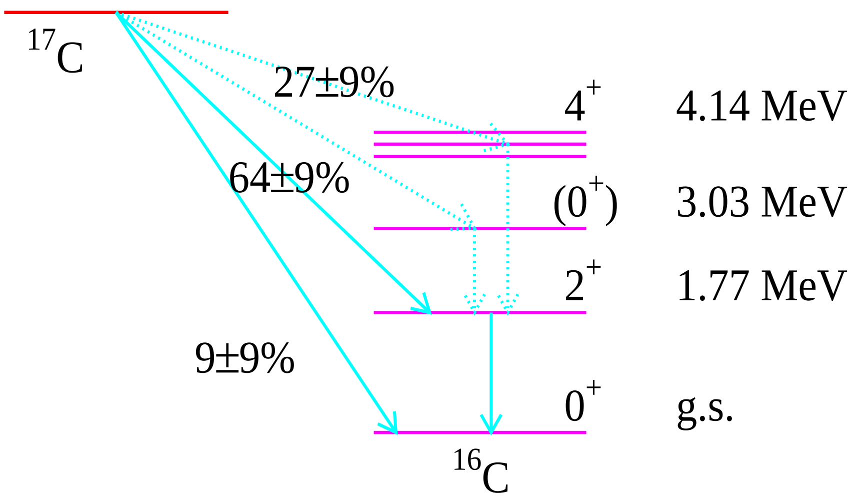
- **p($^{11}$Be,$^{10}$Be)d**, GANIL, S. Fortier et al.
- **Knockout reaction**, MSU, T. Aumann et al.
- **Magnetic moment**, ISOLDE, W. Geithner et al.

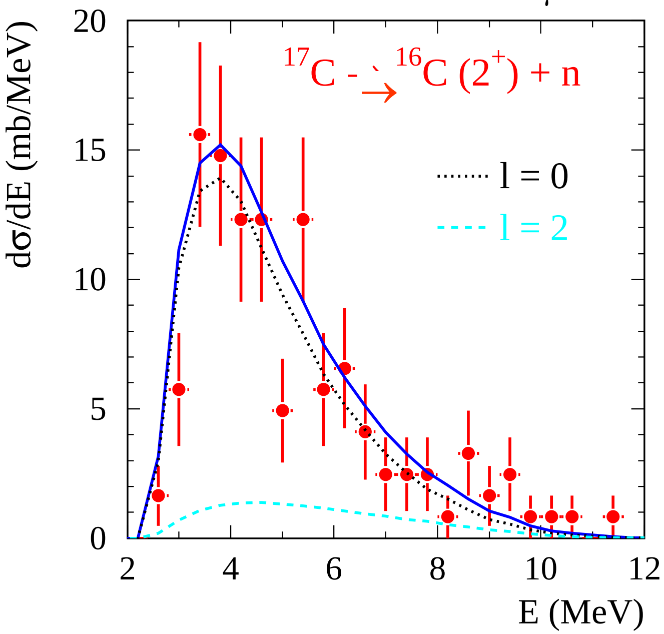
**Data: LAND-FRS@GSI**

**R. Palit et al., to be published**

# Coulomb breakup of $^{17}C$




⇒ Dominant ground state configuration

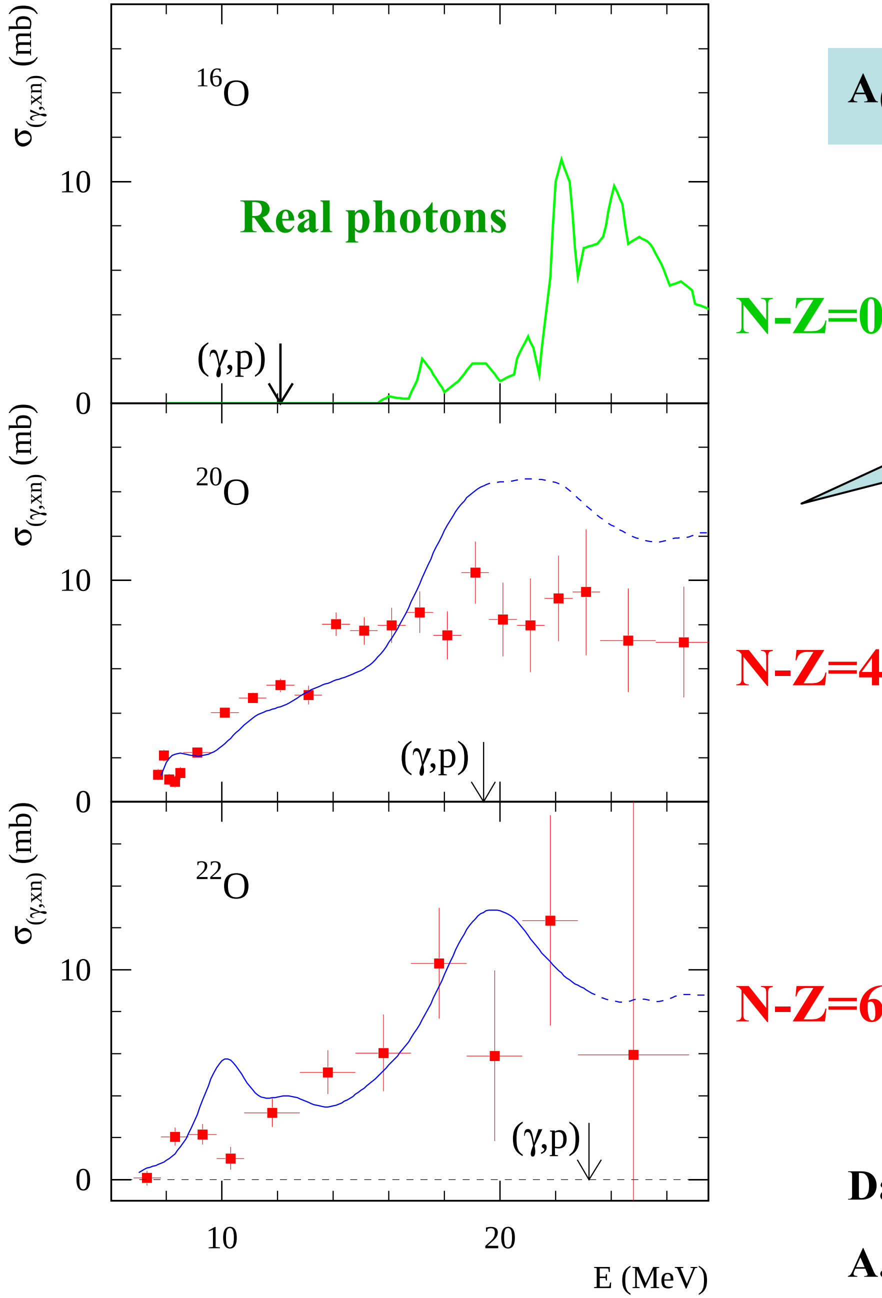
$|^{16}C(2^+)\otimes\nu_{s,d}>$

⇒ ground-state spin $I^\pi = 1/2^+$ excluded

**Data: LAND-FRS@GSI**

**U. D. Pramanik et al., subm. to Phys. Lett**

# Dipole Strength Distribution of n-Rich Nuclei




$^{A}$O (~500 MeV/u) +Pb → $^{A-x}$O+γ+*xn*

⇒ Photo-neutron cross sections from virtual photons

⇒ Low-lying dipole strength

⇒ Fragmentation of GDR strengt

? Collective soft mode ?

Large-scale shell model calculation

H. Sagawa, T. Suzuki,

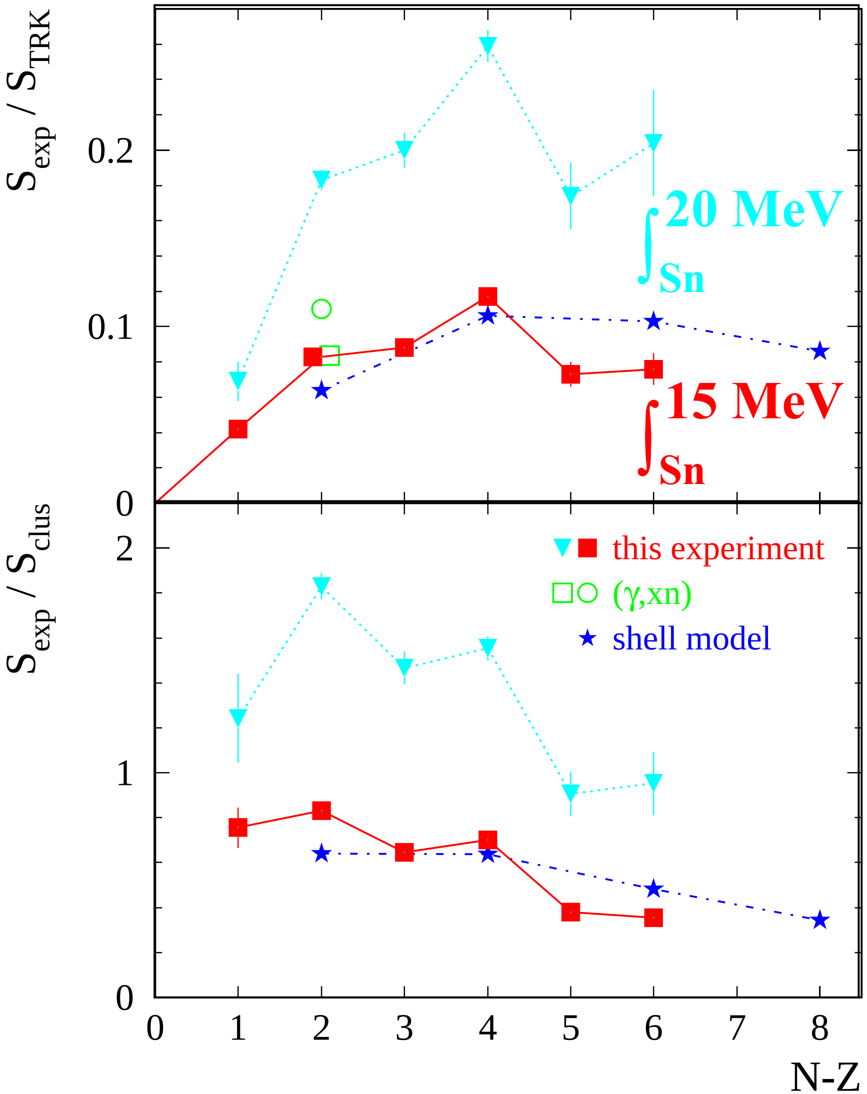
Phys. Rev. C 59 (1999) 3116

Data: LAND-FRS@GSI

A. Leistenschneider et al., Phys. Rev. Lett. 86 (2001) 54

# Low-Lying E1 Strength of n-Rich Oxygen Isotopes

## ⇒ Integrated strength below the GDR




**Energy-weighted classical dipole sum rule (Thomas Reiche Kuhn)**

$$S_{TRK} = 60\ NZ/A\ \text{mb MeV}$$

**"Cluster" sum rule**
**(valence neutrons ⇔ core)**

$$S_{clus} = Z_c / A_c\ N_h / N \times S_{TRK}$$

**⇒ no clear evidence for collective soft mode**

**Data: LAND-FRS@GSI**

**A. Leistenschneider et al., PRL 86 (2001) 5442**

# LAND-FRS Collaboration (S135, S188)

**Göteborg/Aarhus**

L.Axelsson, C.Forssen
B. Jonson, M.Meister
K.Markenroth, T.Nilsson
G.Nymann, K.Riisager

**U. Krakow**

R.Kulessa
E.Lubkiewicz,
A.Kliemkiewicz
W.Prokopowicz
W.Walus, W.Wajda

**Kurch. Moscow**

D.Aleksandrov
L.Chulkov, I.Mukha
Pribora

**TU Darmstadt**

M.Pantea A.Richter
G.Schrieder, H.Simon

**LMU München**

P.Reiter

**GSI**

| LAND: | FRS: |
|---|---|
| T.Aumann | H.Geissel |
| U.D.Pramanik | M.Hellström |
| H.Emling | G.Münzenberg |
| K.Jones | K.Sümmerer |
| P.Adrich | F.Nickel |

**U. Mainz**

K.Boretzky
LeHong Khiem
J.V.Kratz, C.Nocifo

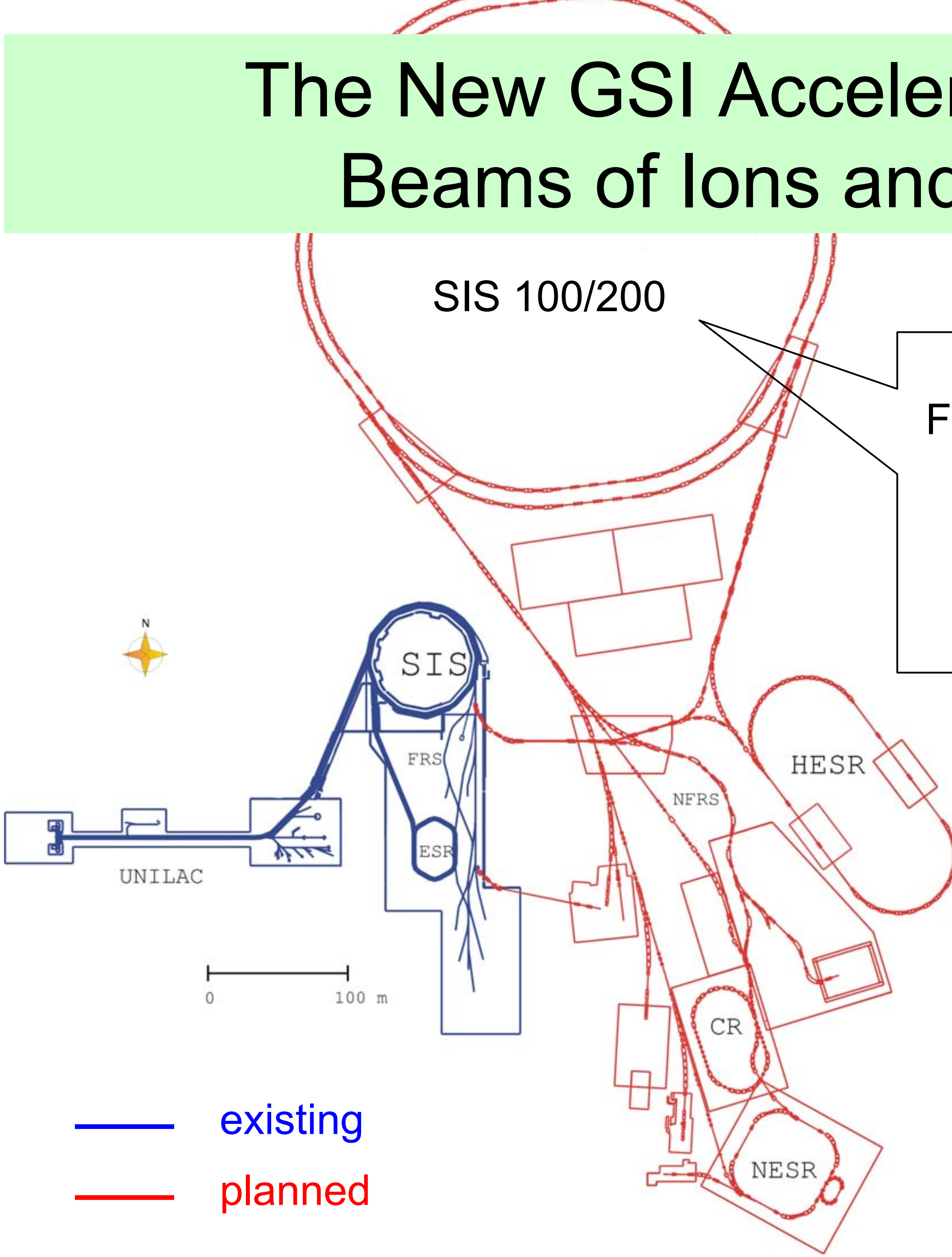
**U.Frankfurt**

Th.W.Elze, S.Ilievsk
A.Leistenschneider
R.Palit

**Madrid, Santiago**

MJG. Borge, D. Cortina,
O.Tengblad.

# The New GSI Accelerator Facility for Beams of Ions and Antiprotons

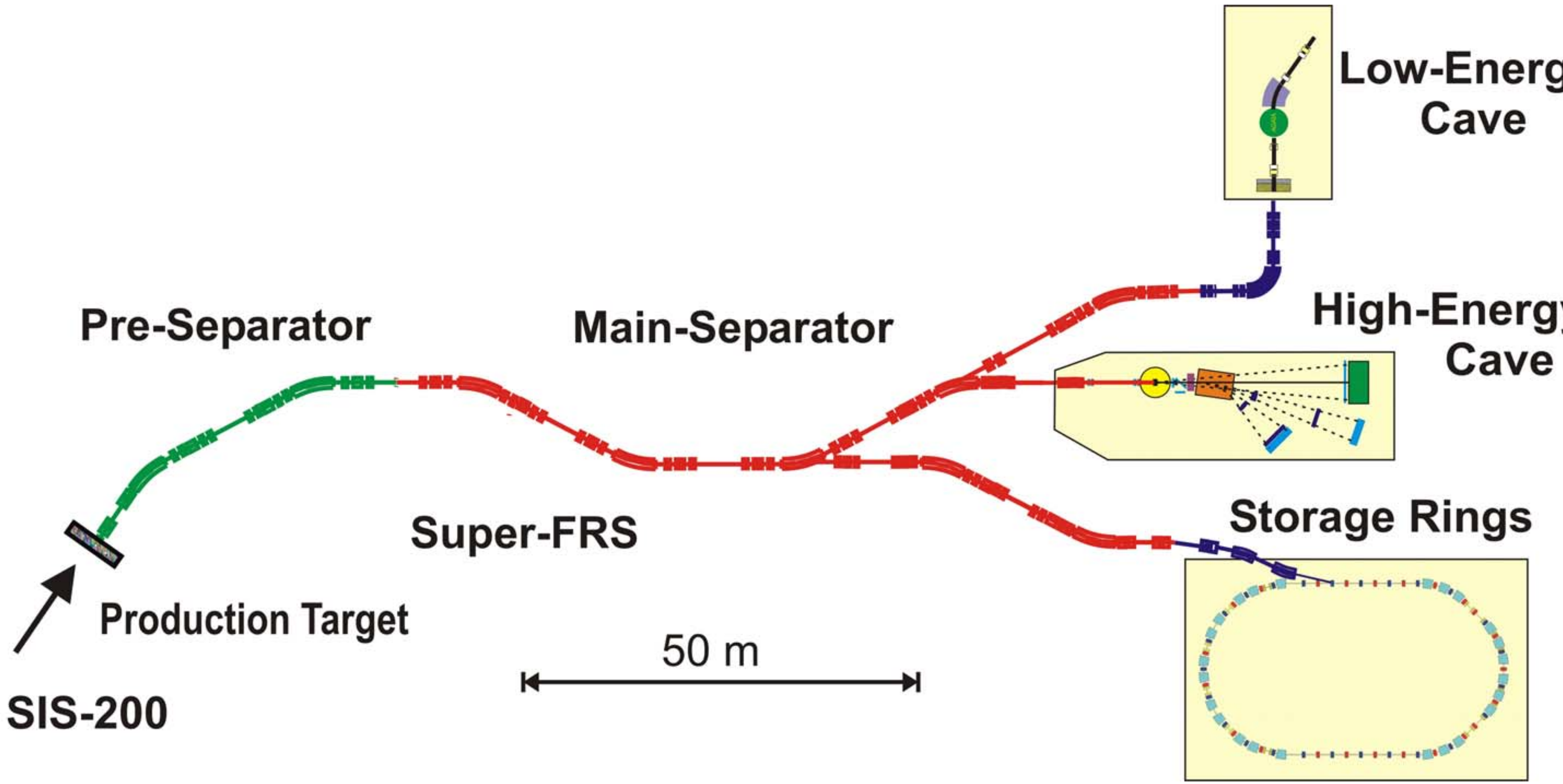



High-Intensity Synchrotron
Fast cycling superconducting magnets
60 GeV protons
23 GeV/u $U^{92+}$
30 GeV/u $Ne^{10+}$
1 GeV/u $U^{28+}$

Four major research areas:

- **Nuclei far from stability**
- Hadron spectroscopy ( $\bar{p}$ )
- Compressed nuclear matte
- Plasma and Atomic Physic

# A New In-Flight Exotic Nuclear Beam Facility



# R$^3$B: A next-generation experimental setup for Reaction studies with Relativistic Radioactive Beams

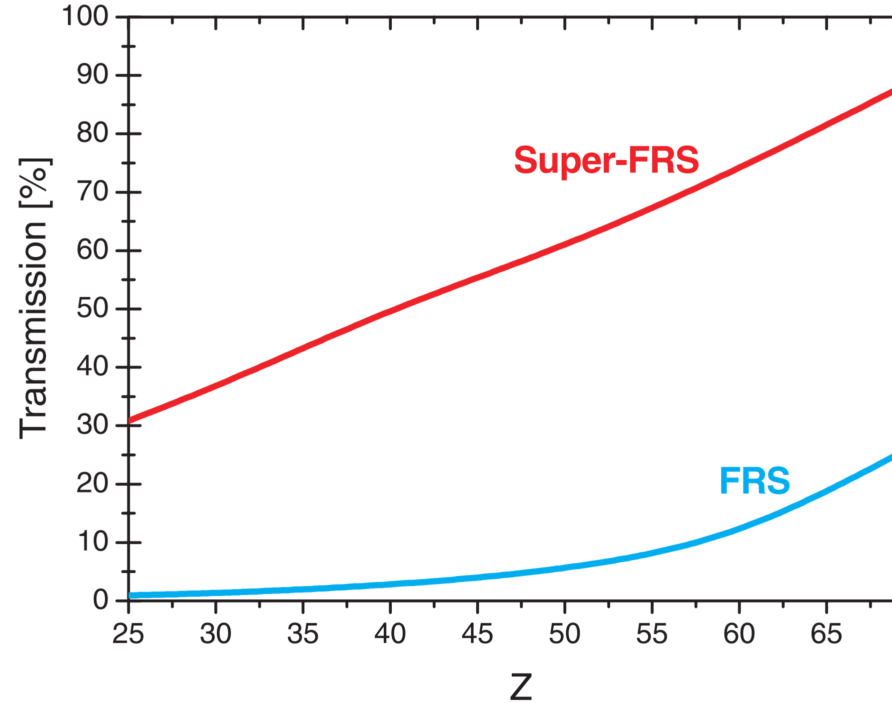
- EU-project: Enhancing Access to Research Infrastructures
  Improving Human Potential Programme

- Collaboration:
  GSI (coordination)
  GANIL, France
  Chalmers University, Sweden
  University Giessen, Germany
  University Krakow, Poland
  CEA Saclay, France
  TU München, Germany
  Univ. Santiago de Compostela, Spain

- Tasks
  - Super-conducting fragment separator
  - High-power production target
  - Large-acceptance magnetic spectrometer
  - Liquid-hydrogen target
  - Advanced detector systems
  - High-speed data-acquisition
  - Simulations of key experiments

- Total Cost: 1.6 M€ EU funds: 0.8 M€

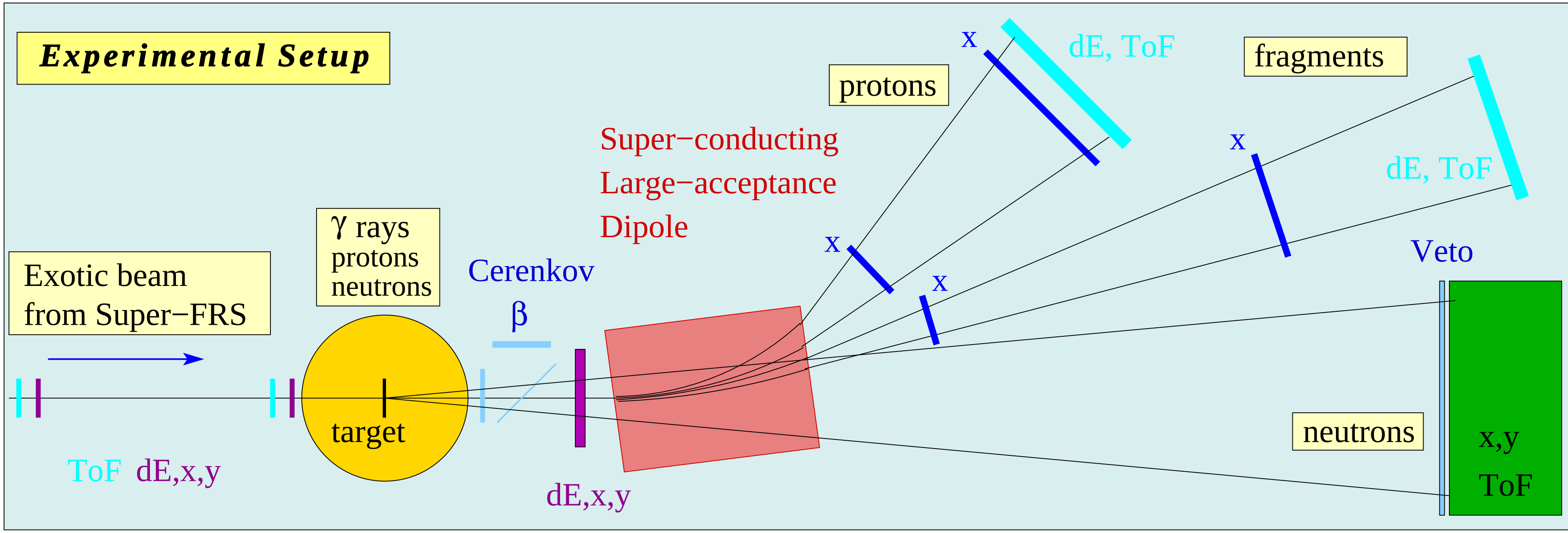
A large-acceptance SUPERconducting FRragment Separator SUPER-FRS




| Facility | $\Delta p/p$ | $\Delta\Phi_x$ | $\Delta\Phi_y$ | Resolving Power |
|---|---|---|---|---|
| FRS ($B\rho_{max} = 18$ Tm) | ± 1 % | ± 13 mrad | ± 13 mrad | 1500 for 20 π mm mrad |
| Super-FRS ($B\rho_{max} = 20$ Tm) | ± 2.5 % | ± 40 mrad | ± 20 mrad | 1500 for 40 π mm mrad |

# R³B: A next-generation experimental setup for Reaction studies with Relativistic Radioactive Beams

**Kinematically complete measurements of reactions with secondary beams**



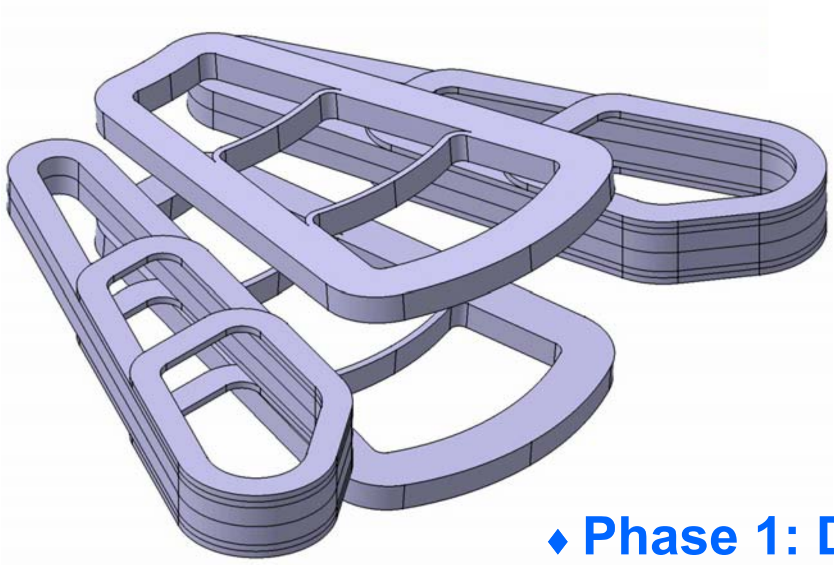

★ Electromagnetic excitations ➤ single-particle structure ➤ soft modes ➤ GDR ➤ B(E2) ➤ astrophysical S-factor

★ Knockout / quasi-free scattering ➤ single-particle structure ➤ unbound states

★ Charge exchange (p,n) ➤ GT strength ➤ spin dipole resonance ➤ neutron skin

★ Other reactions: Fission, Fragmentation, Multifragmentation, Spallation

# A Large-Acceptance Spectrometer for $R^3B$



- ❖ **Superconducting coils**
- ❖ **Active shielding**
- ❖ **High field integral**
- ❖ **Large acceptance**

♦ **Phase 1: Design study (completed)**

✓ Design report available

✓ Positive evaluation by international review committee

✓ Funding: EU ($R^3B$)

♦ **Phase 2: Model coil**

⇒ Test of superconductor

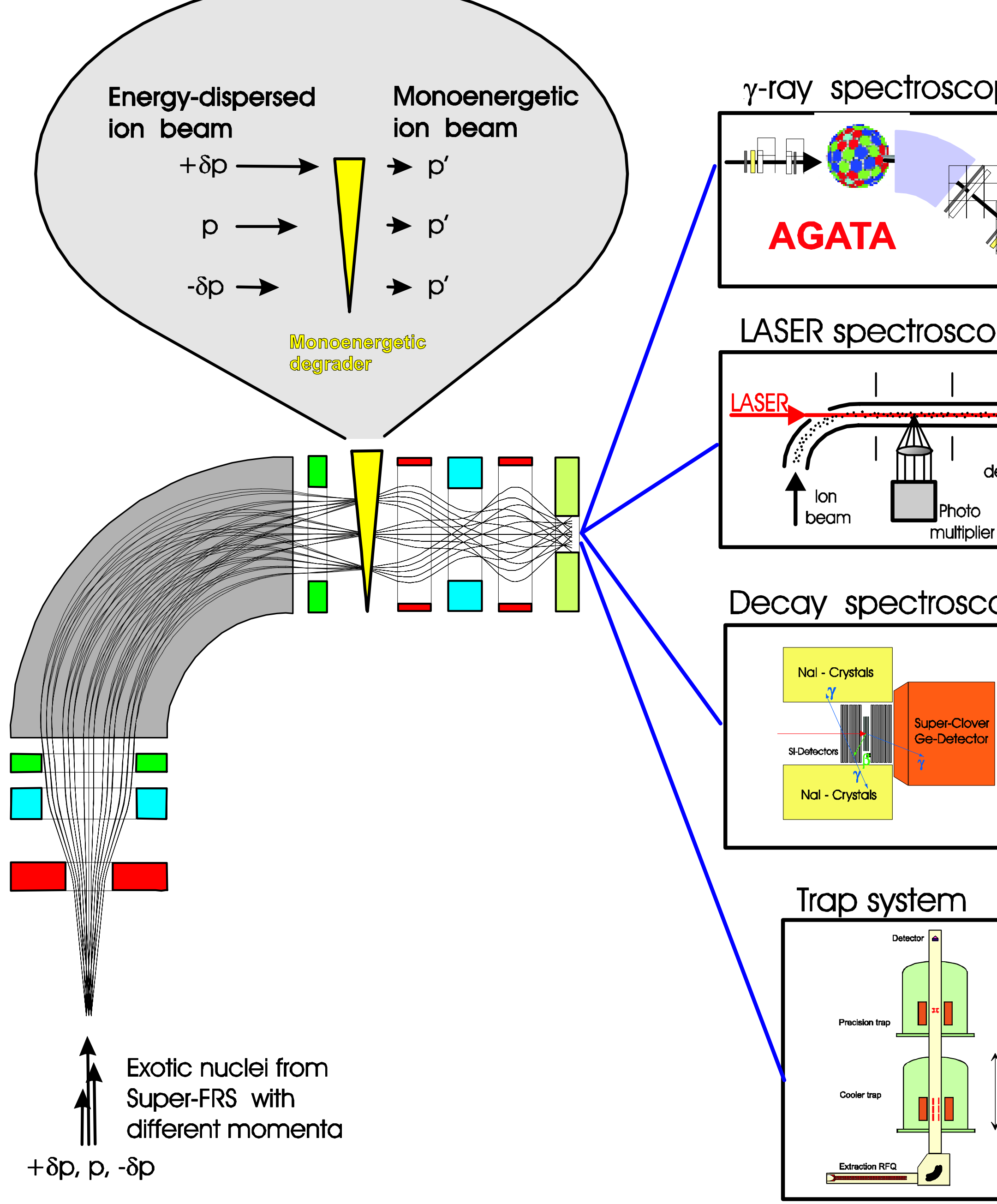
⇒ Test mechanical stress

⇒ Test of quench-protection system

♦ **Phase 3: Construction of full-size magnet**

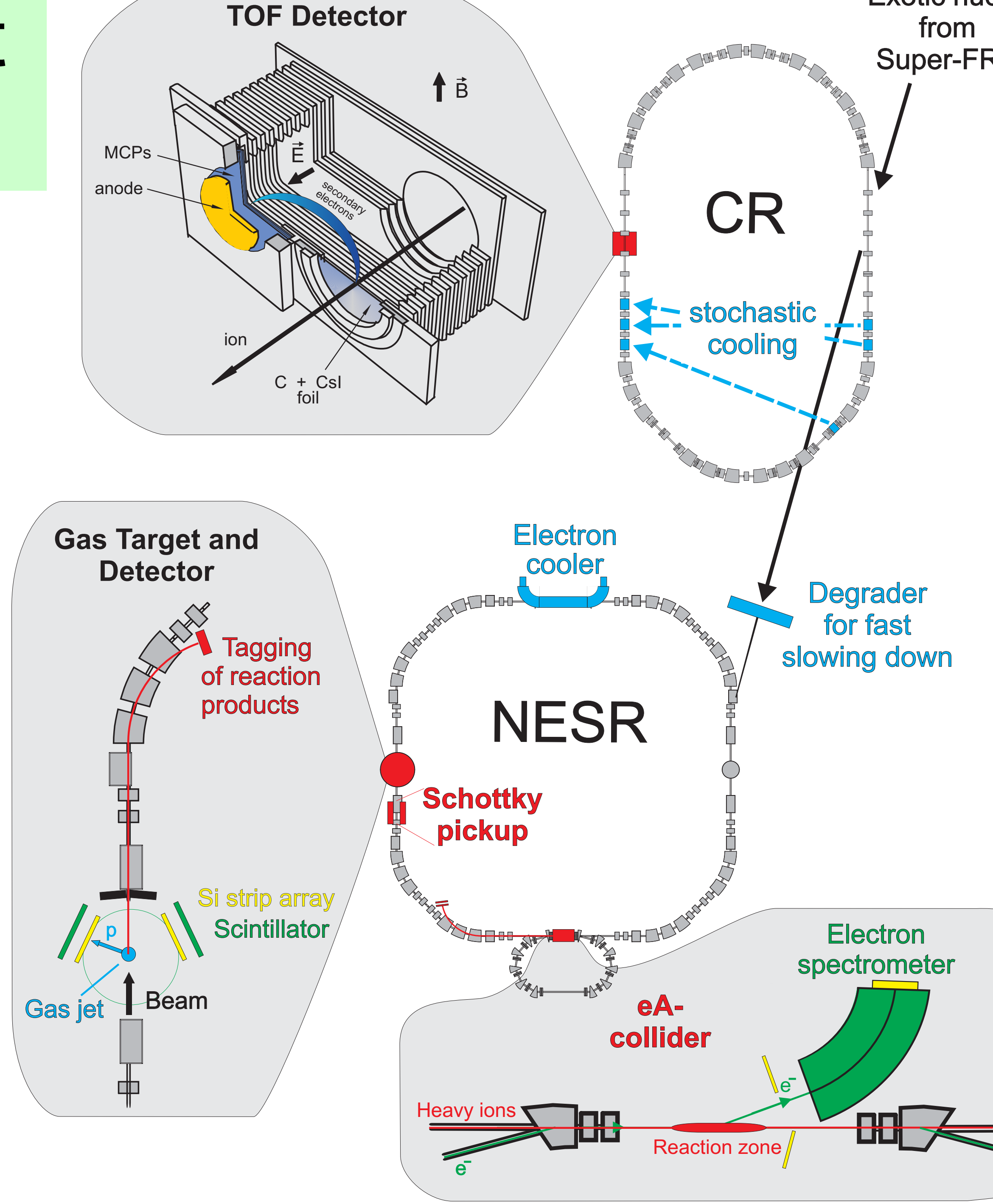
# Experiments with Low-energy and Stopped beams

- Decay spectroscopy
- Reactions near the Coulomb barrier
- Laser spectroscopy
- Ion traps



# Experiments at Storage Rings

- ♦ Mass measurements
- ♦ Reactions with internal targets
  - ➤ Elastic p scatt.
  - ➤ (p,p') (α,α')
  - ➤ transfer
- ♦ Electron scattering
  - ➤ elastic scattering
  - ➤ inelastic



# Conclusion

❖ **Reactions of high-energy radioactive beams are a powerful tool i investigating the structure of short-lived exotic nuclei, even at lowest beam intensities**

Examples discussed:

♦ knockout reactions

➤single-particle structure, unbound states, correlations

♦ electromagnetic excitations

➤ giant-resonance strength, single-particle structure, soft collective modes ?

❖ **The future project at GSI**

➤ **higher intensities**

(primary beam intensity, efficient separation, transportation and injection of radioactive beams into storage rings)

➤ **new experimental methods and concepts**

(e.g. reactions in storage rings, light hadron scattering, $e^-$ - scattering, …)