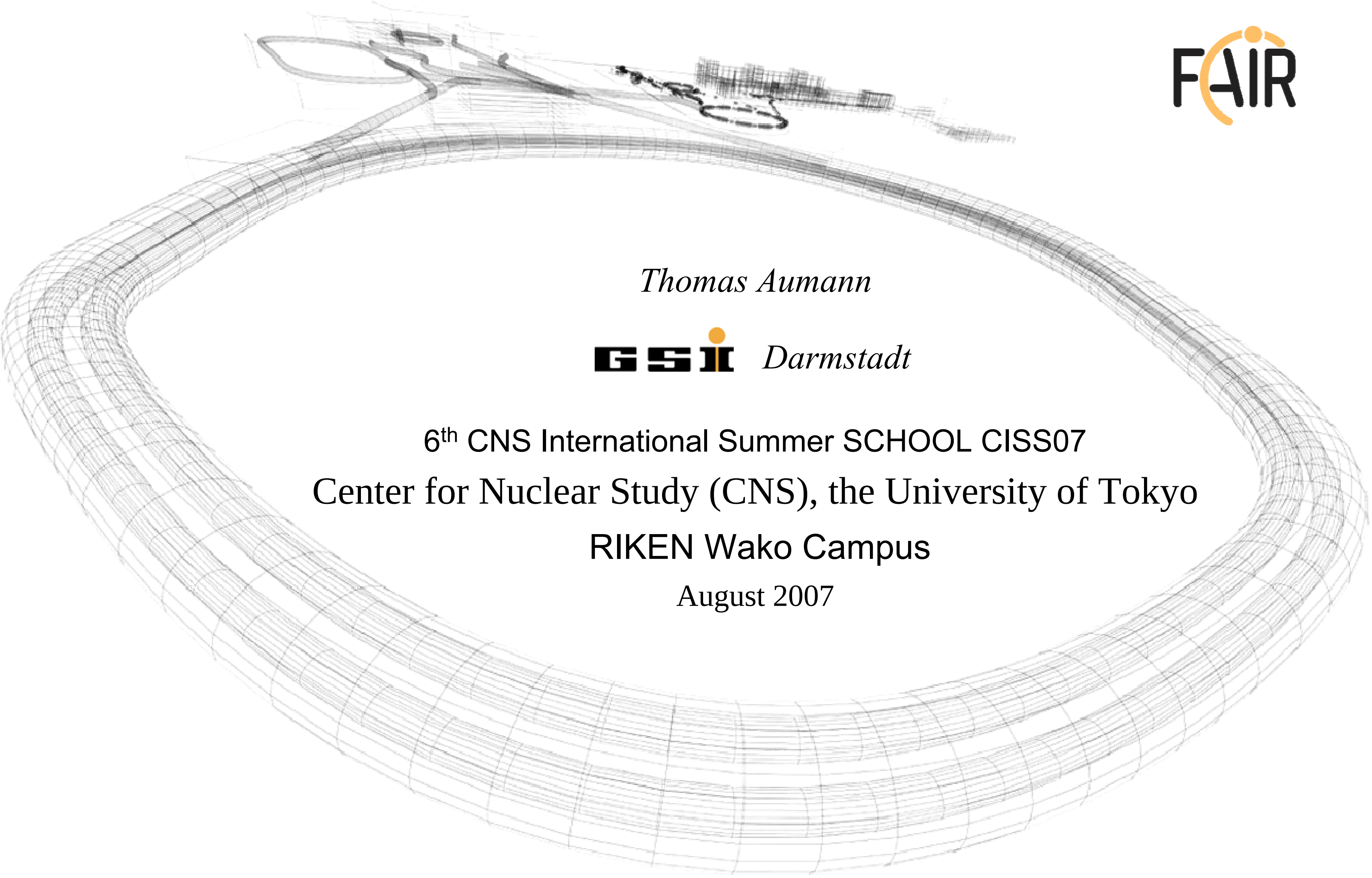
Experiments with High-Energy Radioactive Beams



Thomas Aumann

GSI *Darmstadt*

6th CNS International Summer SCHOOL CISS07

Center for Nuclear Study (CNS), the University of Tokyo

RIKEN Wako Campus

August 2007

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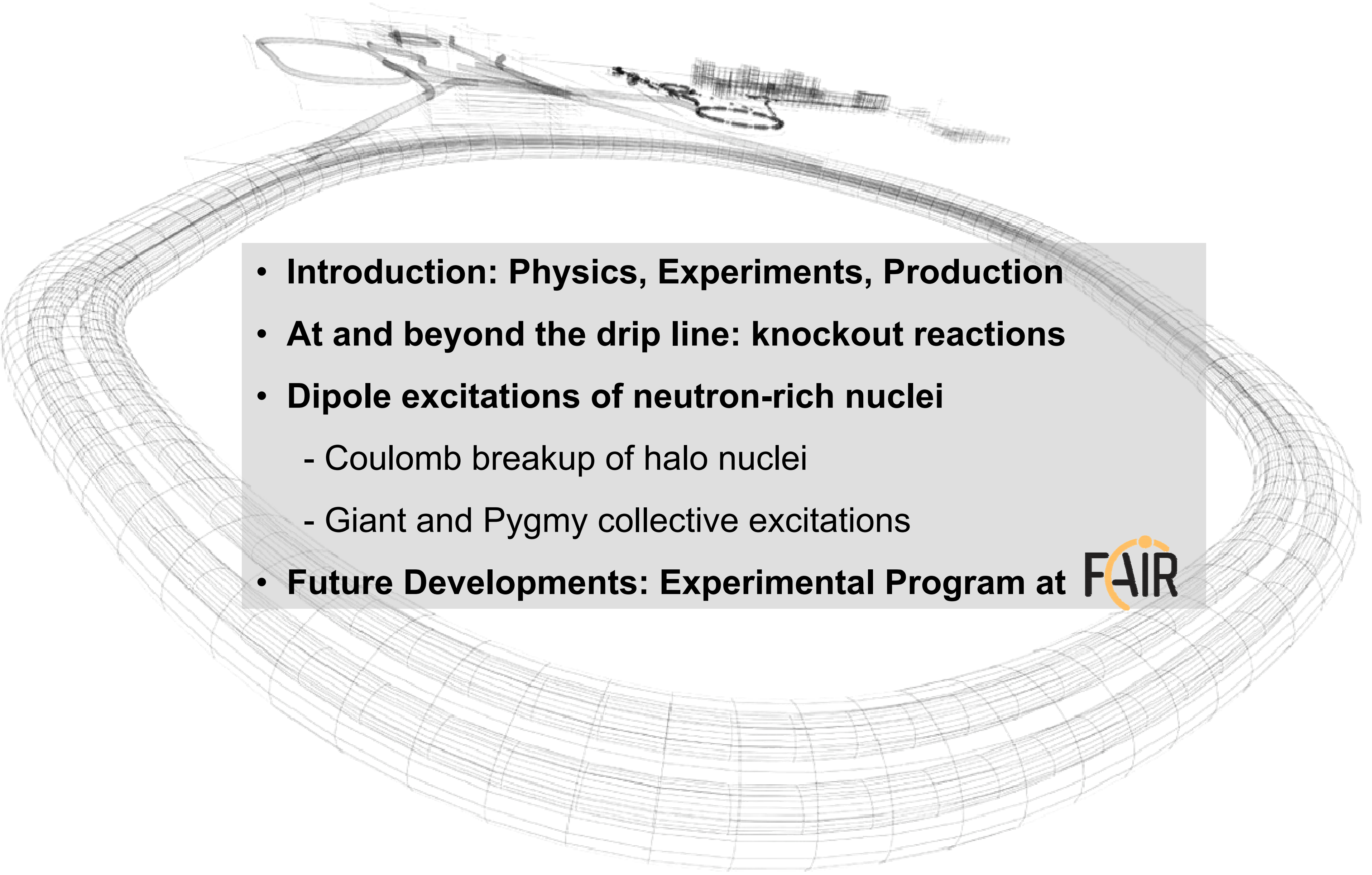
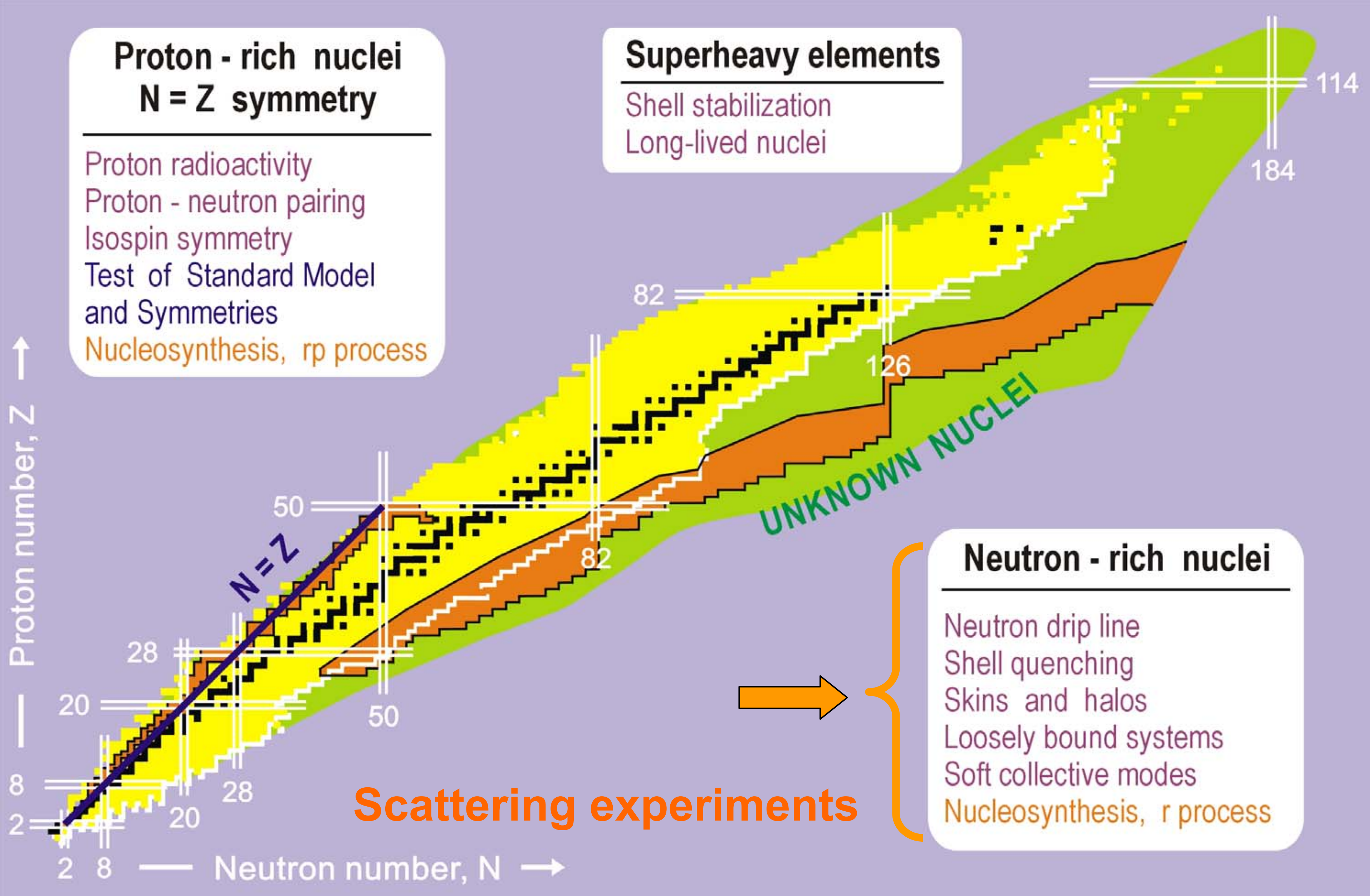


- **Introduction: Physics, Experiments, Production**
- **At and beyond the drip line: knockout reactions**
- **Dipole excitations of neutron-rich nuclei**
  - Coulomb breakup of halo nuclei
  - Giant and Pygmy collective excitations
- **Future Developments: Experimental Program at FAIR**

Physics of exotic nuclei



Proton - rich nuclei
N = Z symmetry

- Proton radioactivity
- Proton - neutron pairing
- Isospin symmetry
- Test of Standard Model and Symmetries
- Nucleosynthesis, rp process

Superheavy elements

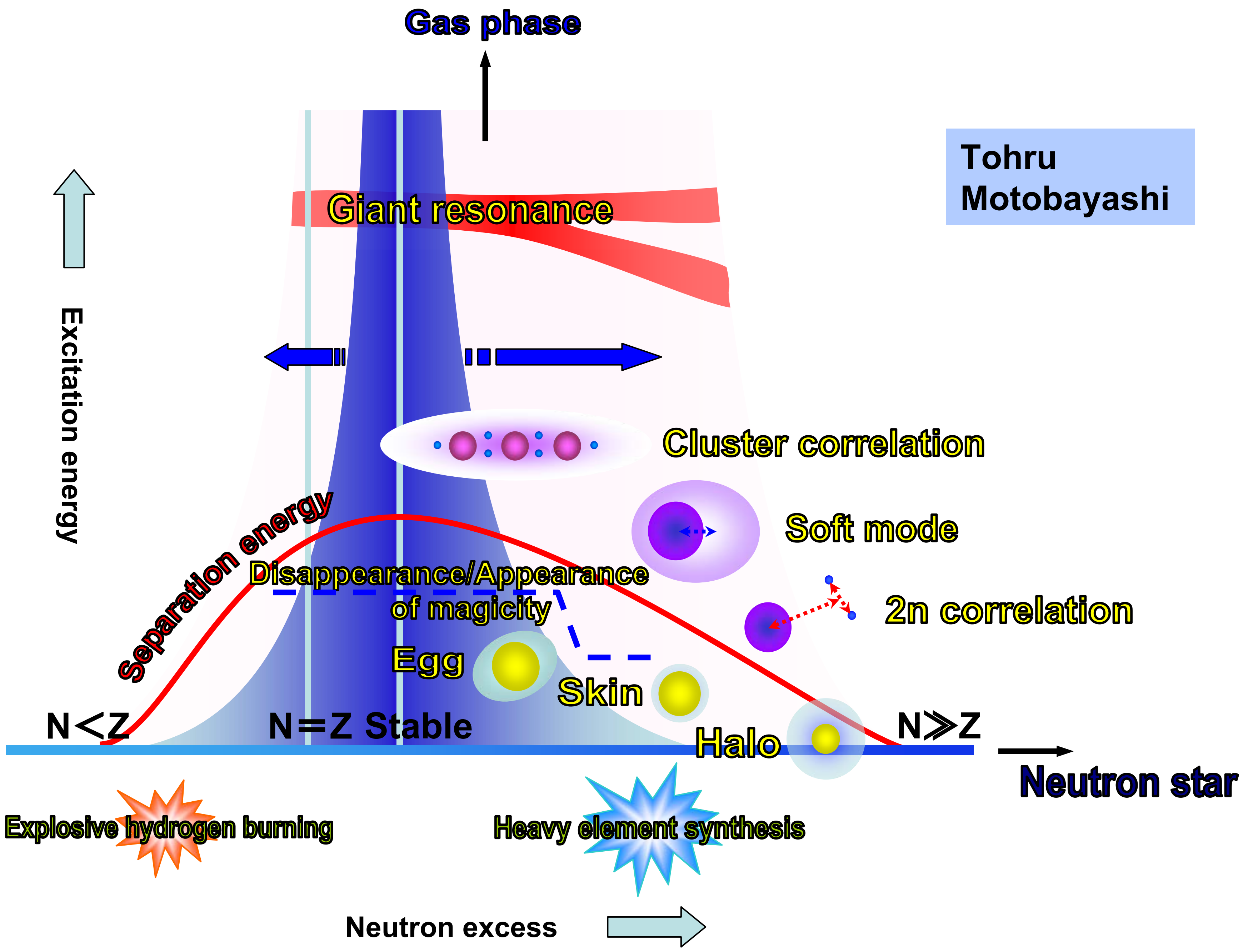
- Shell stabilization
- Long-lived nuclei

Neutron - rich nuclei

- Neutron drip line
- Shell quenching
- Skins and halos
- Loosely bound systems
- Soft collective modes
- Nucleosynthesis, r process

Scattering experiments

Tohru Motobayashi



Gas phase

Excitation energy

Giant resonance

Cluster correlation

Soft mode

2n correlation

Separation energy

Disappearance/Appearance of magicity

Egg

Skin

Halo

N<Z

N=Z Stable

N≫Z

Neutron star

Explosive hydrogen burning

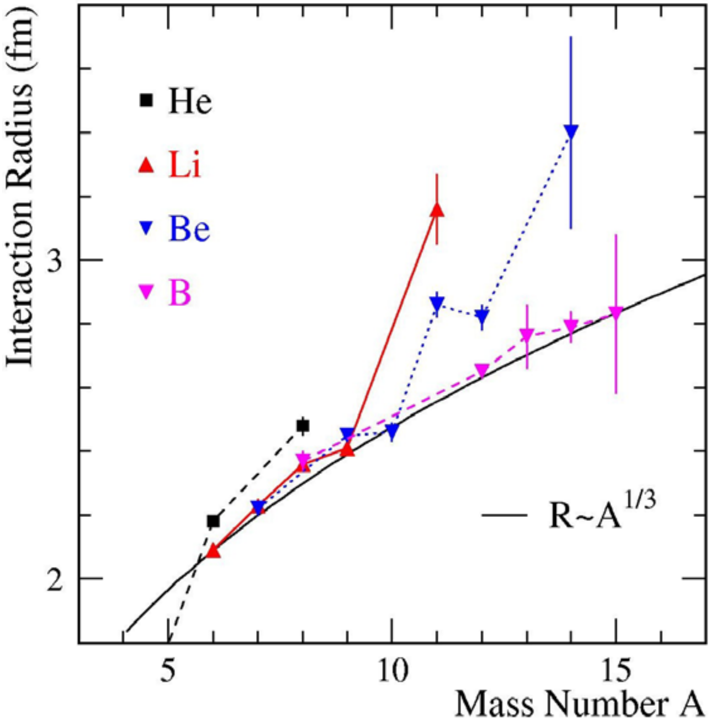
Heavy element synthesis

Neutron excess

First reaction experiments with relativistic radioactive beams: Discovery of the halo nuclei

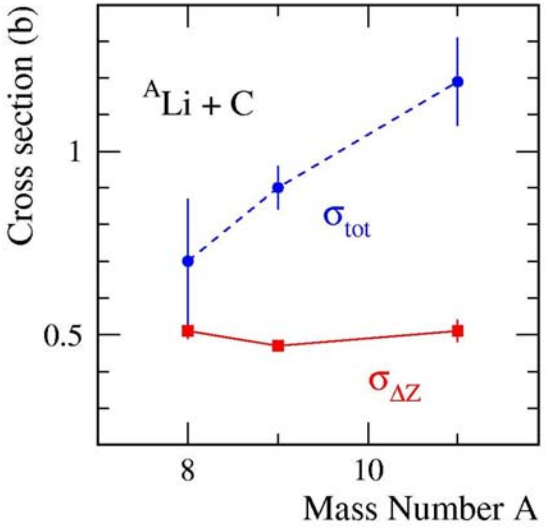
Total reaction cross sections

→ Interaction radii



Bevalac@LBL, I. Tanihata et al.,
PRL 55 (1985) 2676, PLB 206 (1988) 592

Cross sections for charge-changing reactions: ΔZ>0



SATURNE@Saclay
B. Blank et al.,
Z.Phys. A 343
(1992) 375

Quadrupole moment

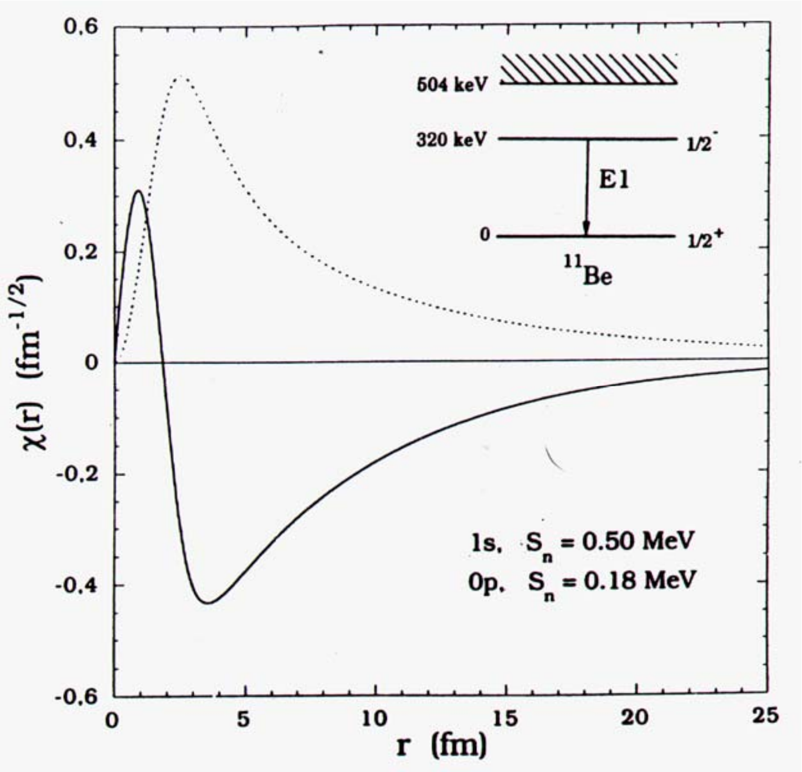
$Q(^{11}Li) \approx Q(^{9}Li)$

ISOLDE@CERN,
E. Arnold et al., Phys.
Lett. B 281 (1992) 16

⇒ Spatially extended neutron-density distribution (Halo)

first theoretical interpretation: G. Hansen and B. Jonson, Europhys. Lett. 4 (1987) 409

The first experimental hint ?: The ^{11}Be neutron halo



Hansen, Jensen, Jonson,

Annu. Rev. Nucl. Part. Sci. 45 (1995) 591

<u>E1 transition in ^{11}Be</u>

Millener et al., Phys. Rev. C 28 (1983) 497:

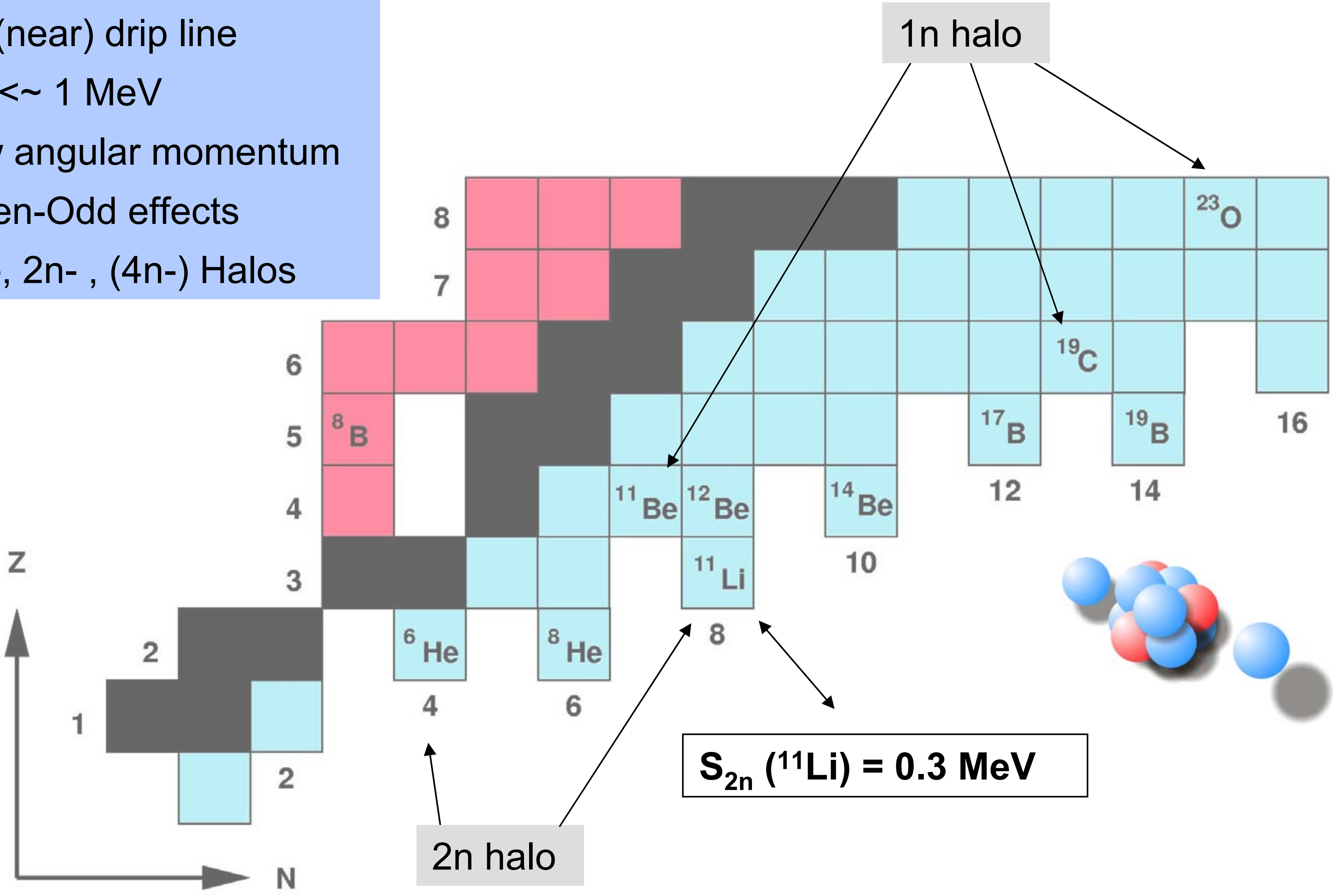
Lifetime τ = 166(15) fs

fastest known E1 transition between bound states

A new phenomenon at the neutron drip line: Halo nuclei

Neutron halo nuclei :

- At (near) drip line
- S_n <~ 1 MeV
- low angular momentum
- Even-Odd effects
- 1n-, 2n- , (4n-) Halos

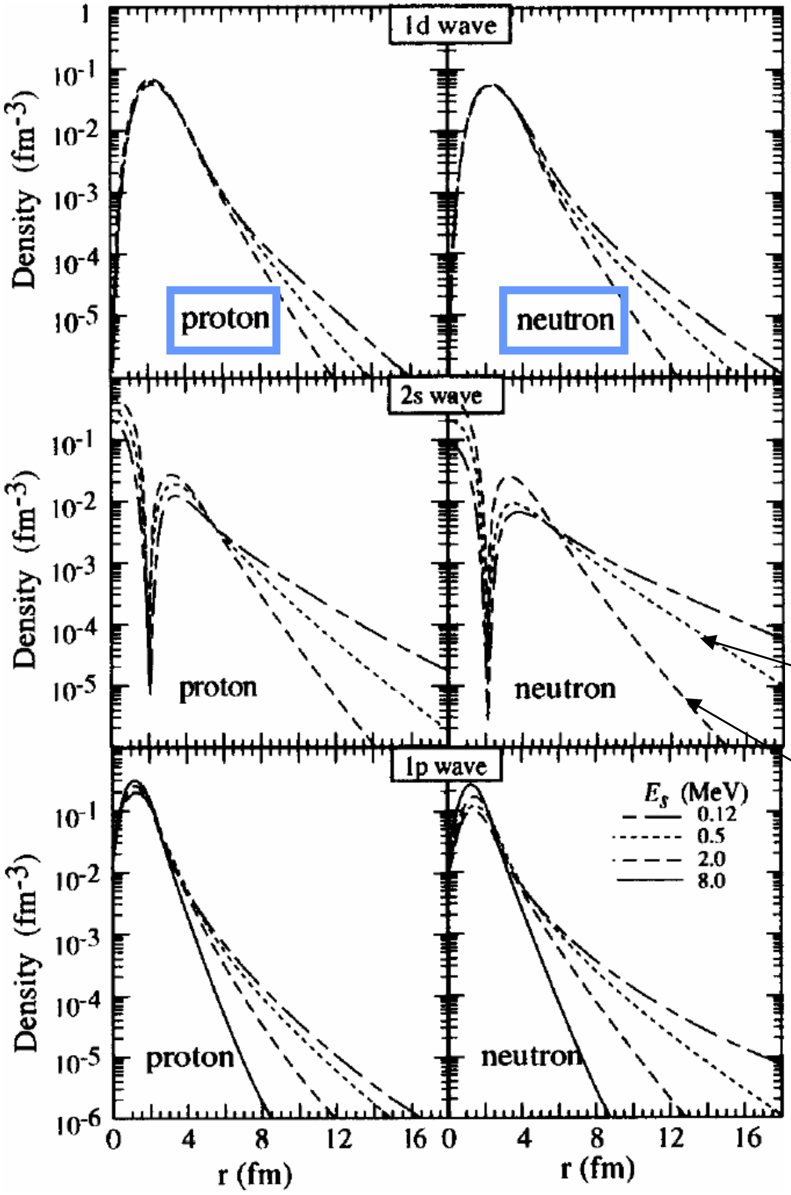


1n halo

2n halo

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

Single-particle density distributions



ℓ=2

ℓ=0

ℓ=1

S_n=0.5 MeV

S_n=8.0 MeV

dependence on

- separation energy S_n
- angular momentum ℓ
- charge

asymptotic decay of the wave function for ℓ=0:

$$\chi(r) = \exp(-\kappa r)$$

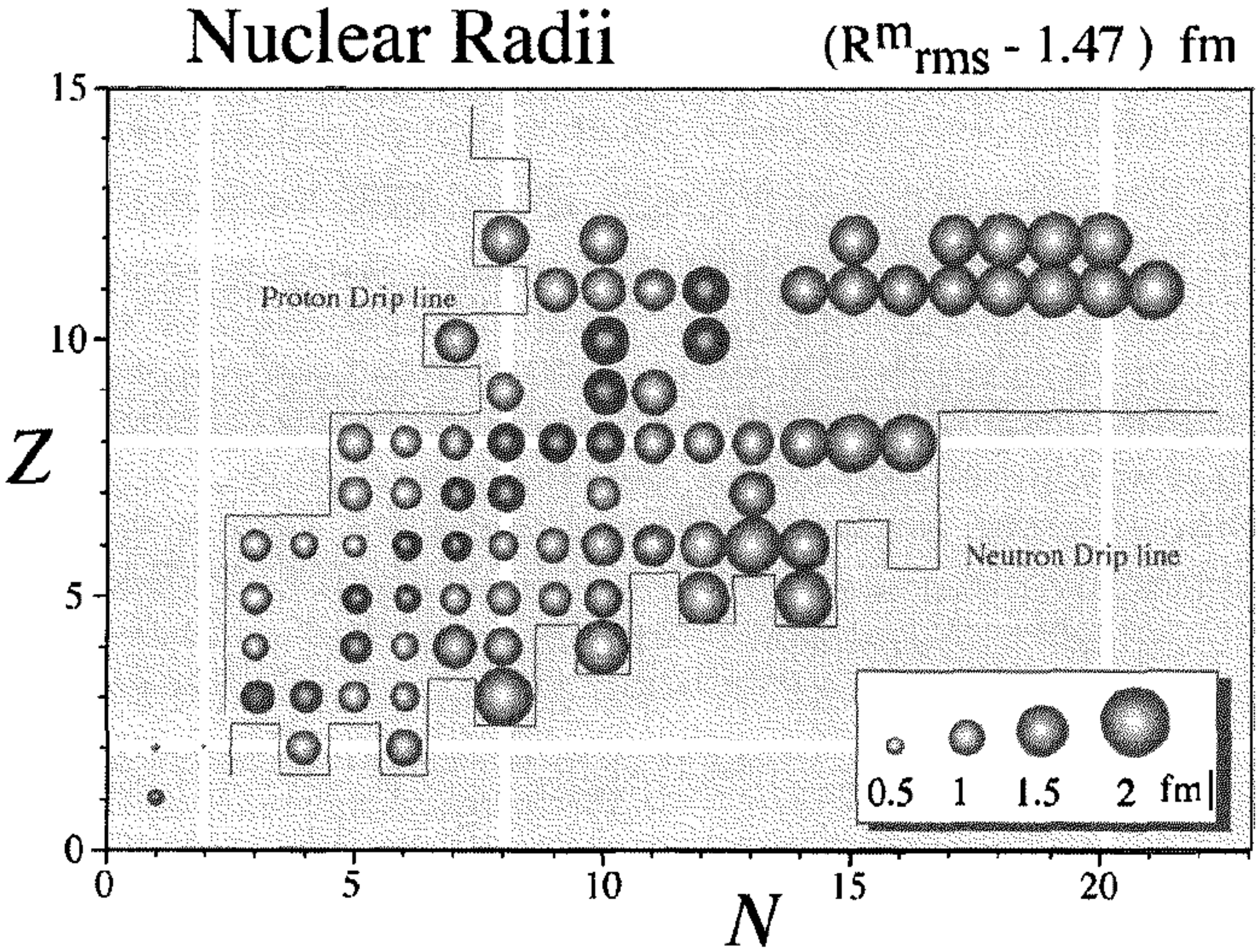
with

$$\kappa = \sqrt{2\mu S_n} / \hbar$$

Wave functions calculated for a Woods-Saxon potential (Z=4, N=3)

I. Tanihata, J.Phys. G 22 (1996) 157

Matter Radii
extracted from total interaction cross section measurements

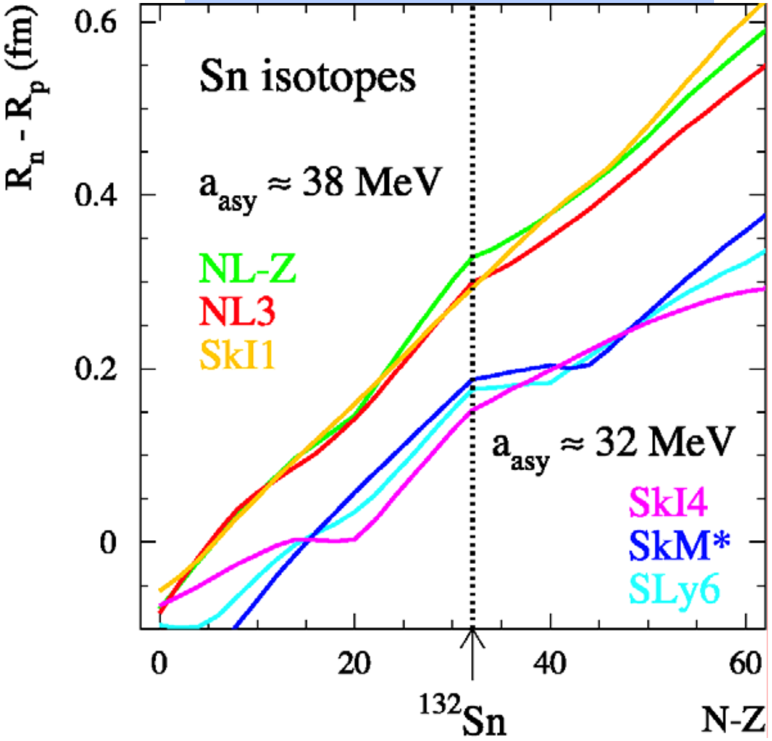


~~$R \sim A^{1/3}$~~

Isao Tanihata, Nucl. Phys. A654 (1999) 235

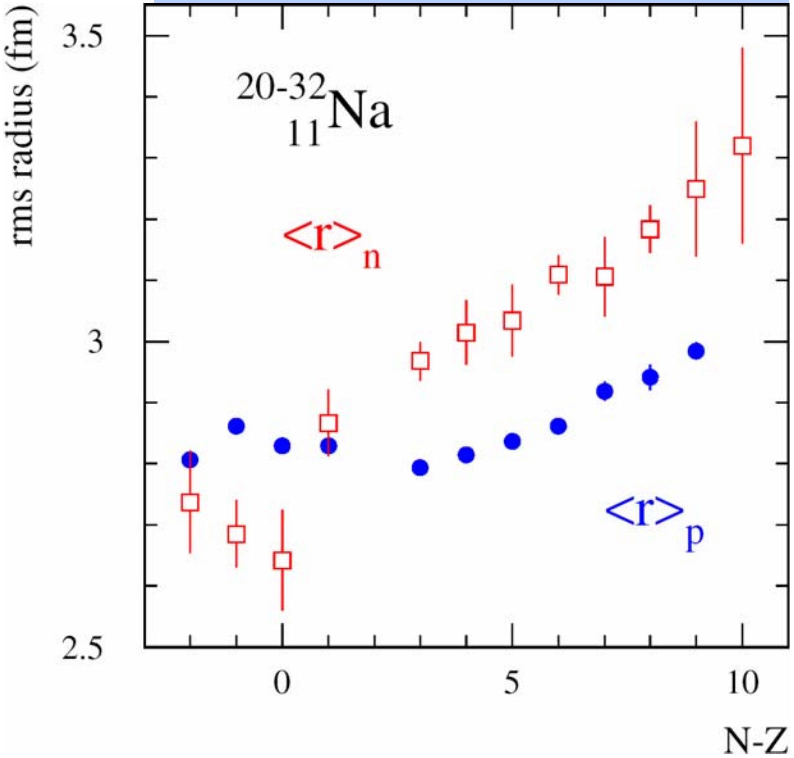
Appearance of a neutron skin in neutron-rich nuclei

Theoretical prediction



Relativistic (NL) and non-relativistic (Skyrme Sk, SL) mean-field calculations
P.G. Reinhard, priv. comm.

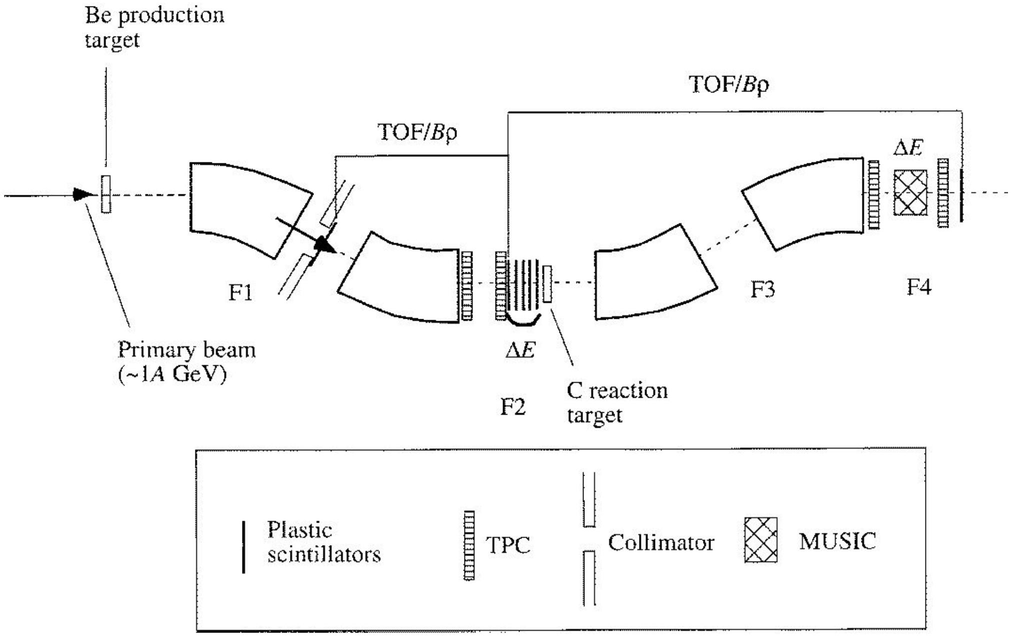
First experimental evidence



Interaction cross section measurement (GSI) plus
Isotope shift measurements (ISOLDE)
T.Suzuki et al., Phys. Rev. Lett. 75 (1995) 3241

Other experimental techniques: IV GDR (isoscalar probe), Spin-dipole resonance (rel. n-skin), **Pygmy dipole**, anti-proton scattering, e- plus p elastic scattering

Total absorption measurements



A. Ozawa et al., Nucl. Phys. A 693 (2001) 32

Black disc model:

$$\sigma = \pi \, [\, R_I(p) + R_I(t) \,]^2$$

→ interaction radius R_I

rms matter radius

$$\sigma = \int 2\pi b db \, [1-T(b)]$$

transmission function T(b)

Glauber:

$$T(b) = \exp\{-\sigma_{NN} \int dz \int d^3r \, \rho_p(\mathbf{r})\rho_t(\mathbf{R}-\mathbf{r})$$

free N-N cross section σ_{NN}, $\mathbf{R}=(\mathbf{b},z)$

density distribution $\rho(r)$

e.g. 2pF: $\rho(r) = \rho_0 \, [1+\exp\{(r-R_0)/a\}]^{-1}$

half density radius R_0, diffuseness a

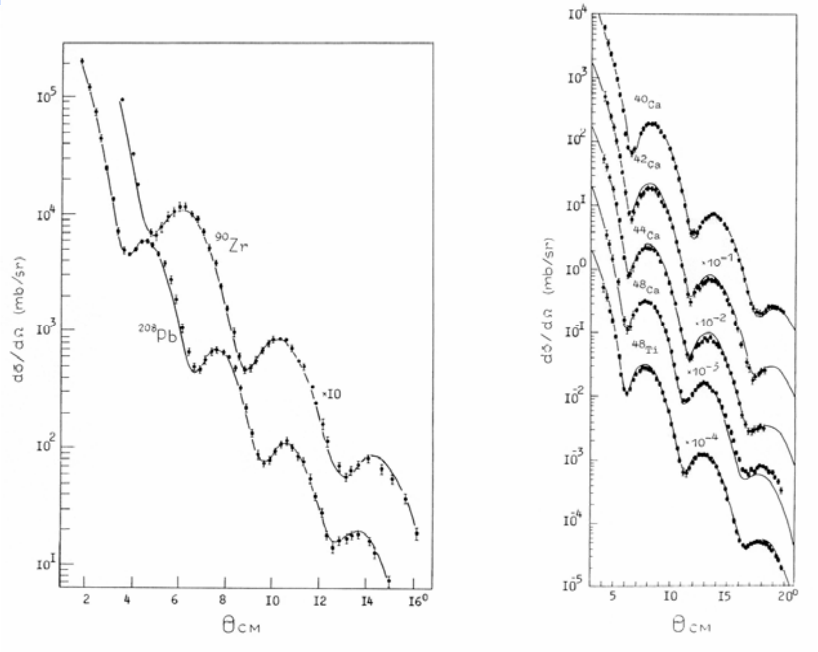
Problem: one measured quantity,
two parameters
(target dependence, energy dependence)

Method applicable down to intensities of 1 ion/s !!!

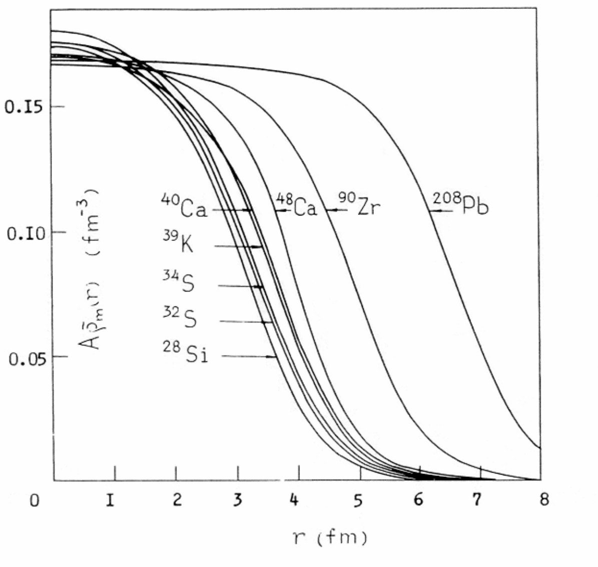
Elastic proton scattering at high energies (~1 GeV)

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

measured differential cross section



deduced matter distribution



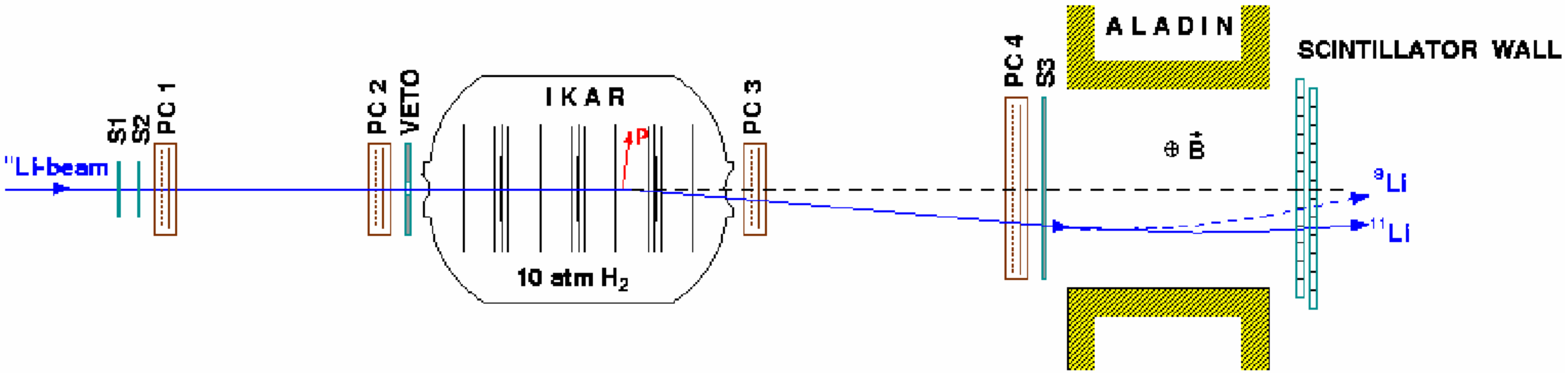
application to exotic nuclei:

→ scattering of radioactive beams off protons (' inverse kinematics ')

→ high-energy radioactive beam (~GeV/nucleon)

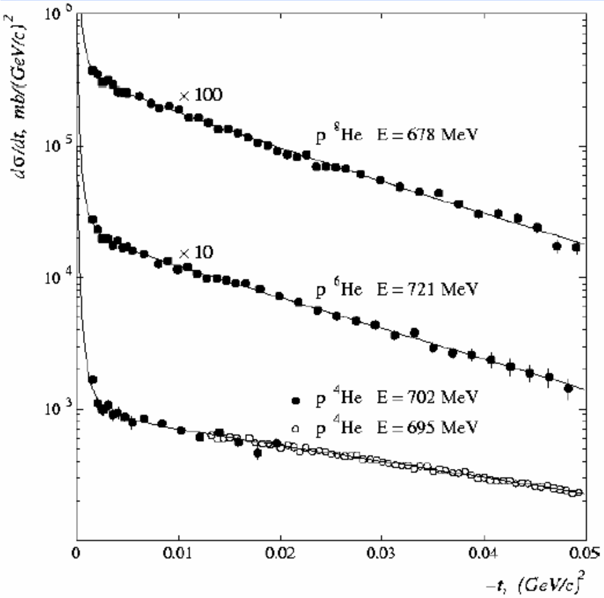
→ measurement of low-energy recoil (target-) proton

Elastic proton scattering on neutron-rich He and Li isotopes: The S105 IKAR experiment at GSI



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

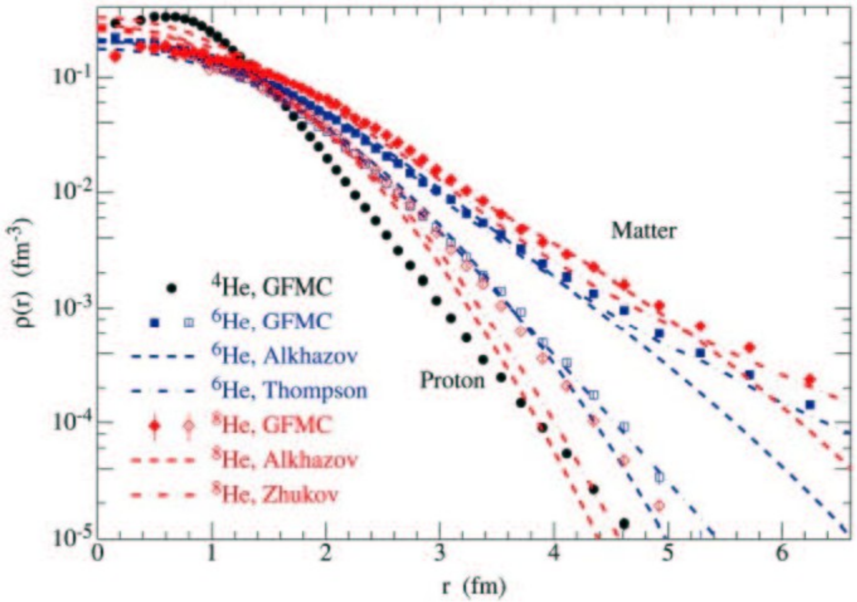
measured differential cross section

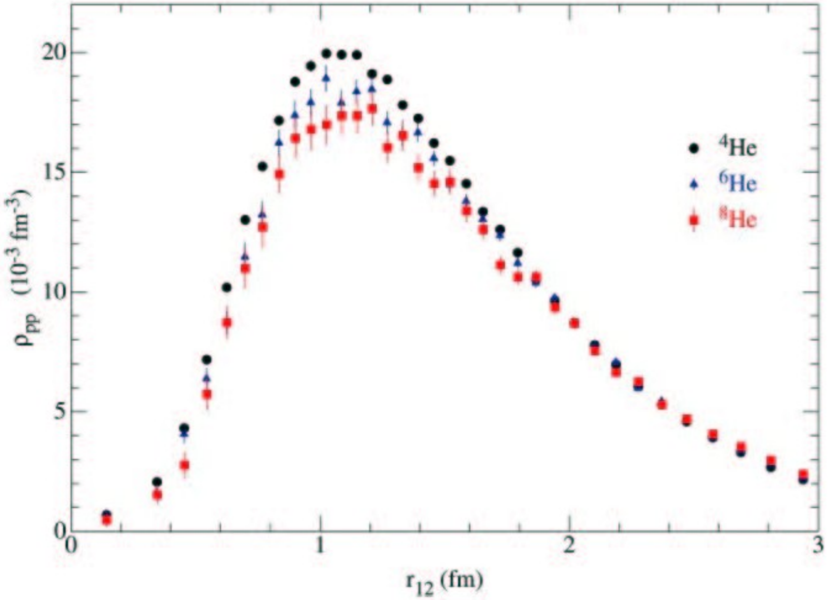


Peter Egelhof

Ab Initio Calculations for n-rich He isotopes

Green’s Function Monte Carlo calculations





⇒ Neutron Halo for ^{6}He and ^{8}He

Matter density distribution
in agreement with
proton elastic scattering data

Proton-proton distribution
function changes only slightly in
^{6,8}He compared to α particle

⇒ Cluster structure

^{6}He: α + 2n (3-body models)

^{8}He: α + 4n

S.C. Pieper and R.B. Wiringa,
Annu. Rev. Nucl. Part. Sci. 51 (2001) 53

Halo Nuclei - Basic Properties - Key Observables

- Symmetry-Energy ~ $(N-Z)^2/A^2$
- ε_f -> 0 : neutron leaks into classically forbidden region
- orbitals of low angular momentum

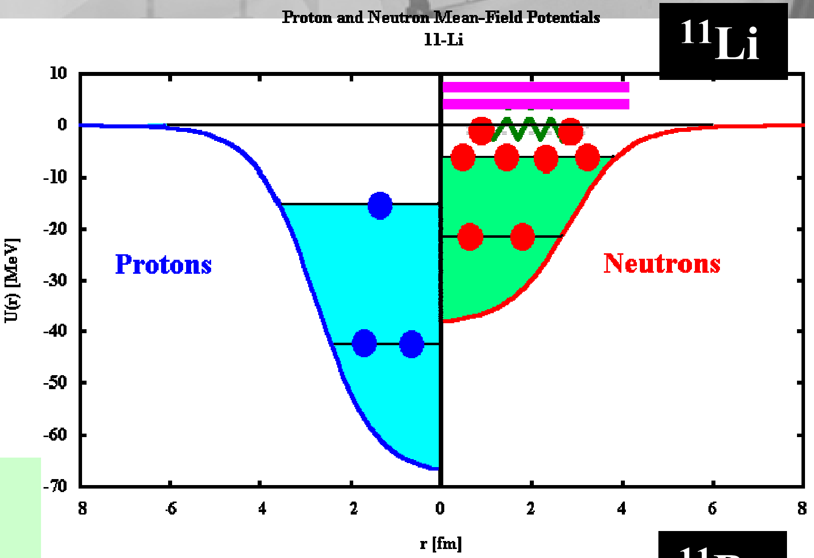
- Large radii and dilute surface
- Low-momentum components
- Bound-state and continuum sector not well separated (very few bound states)
- Pairing / Clusterisation in low-density medium ?
- Decoupling of valence nucleons and core
- Reduced Spin-Orbit splitting (~ 1/r dV/dr)

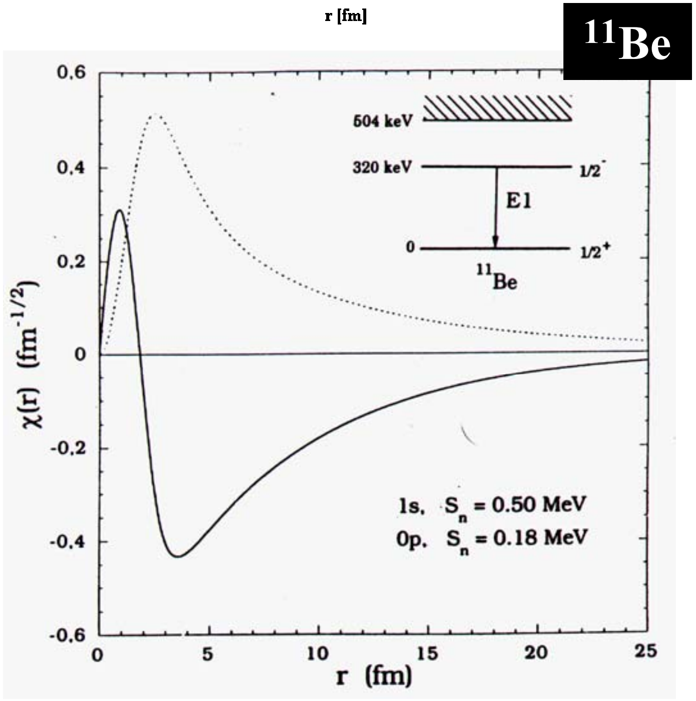
● Single-Particle Structure ?

● Excitation Modes ?

● Specific Reaction Mechanisms ?

● • • •





The collective response of the nucleus: Giant Resonances

Electric giant resonances

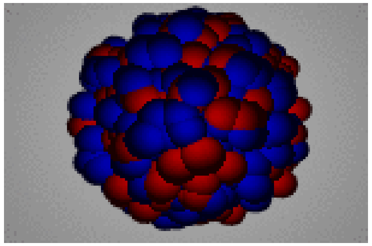
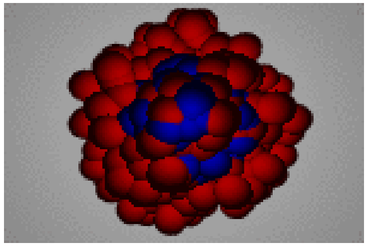
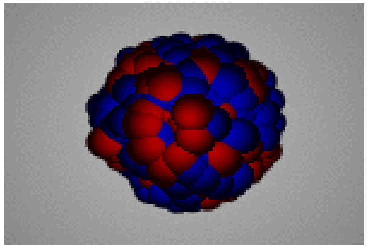
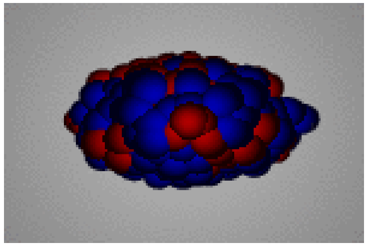
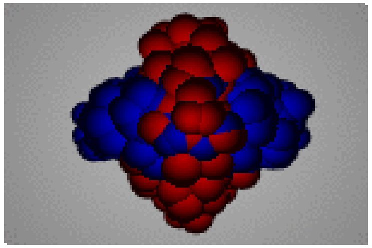
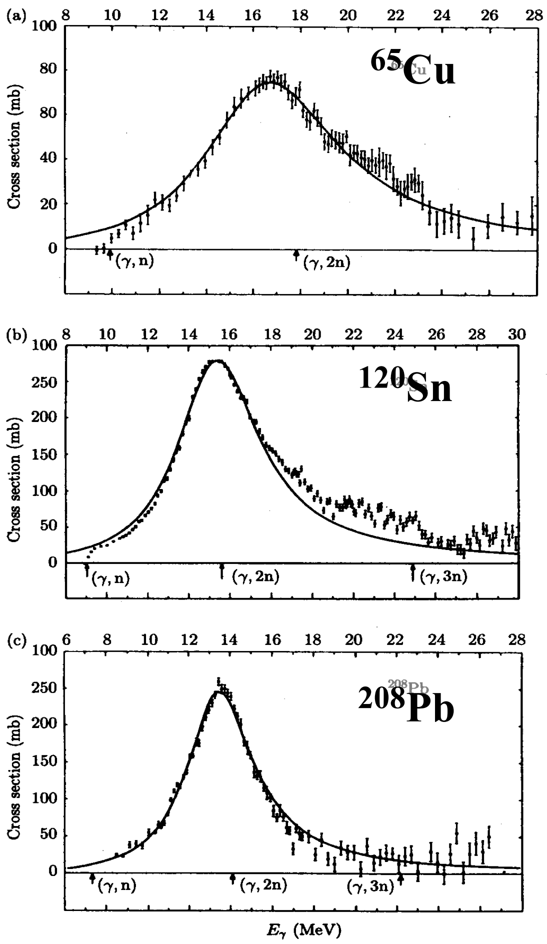
	Isoscalar	Isovector
Monopole (GMR)		
Dipole (GDR)		
Quadrupole (GQR)		

Photo-neutron cross sections

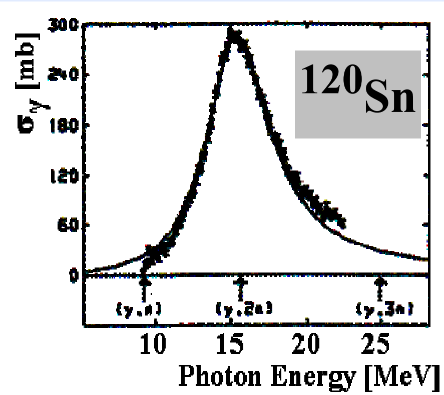


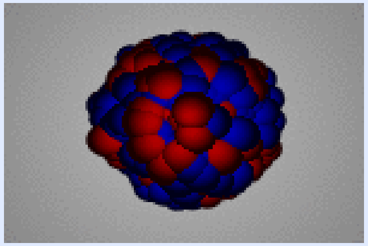
Berman and Fulz, Rev. Mod. Phys. 47 (1975) 47

The dipole response of neutron-rich nuclei

Stable nuclei:

100% of the E1 strength absorbed into the **Giant Dipole Resonance** (GDR)





Neutron-Proton asymmetric nuclei: low-lying dipole strength

! threshold strength

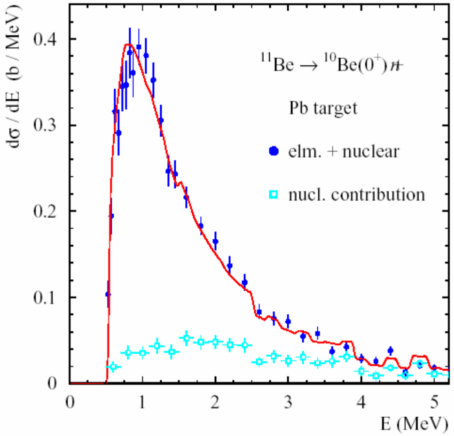
! strong fragmentation

? new collective soft dipole mode

(Pygmy resonance)

non-resonant transitions

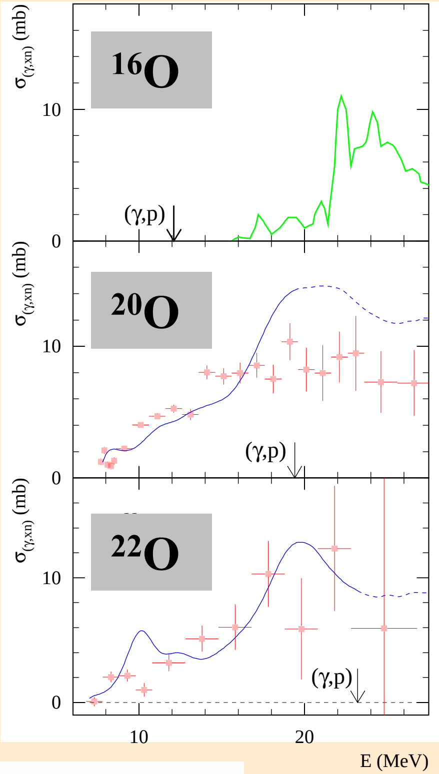
The one-neutron Halo **^{11}Be**



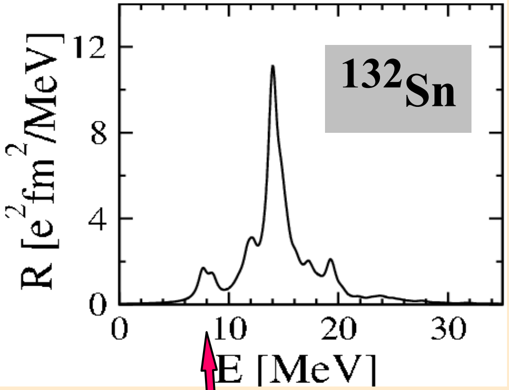
spectroscopic tool:

$$\frac{d\sigma}{dE^*}(I_c^\pi) = (\frac{16\pi^3}{9\hbar c})N_{E1}(E^*)\sum_{nlj} C^2 S(I_c^\pi, n\ell j)$$

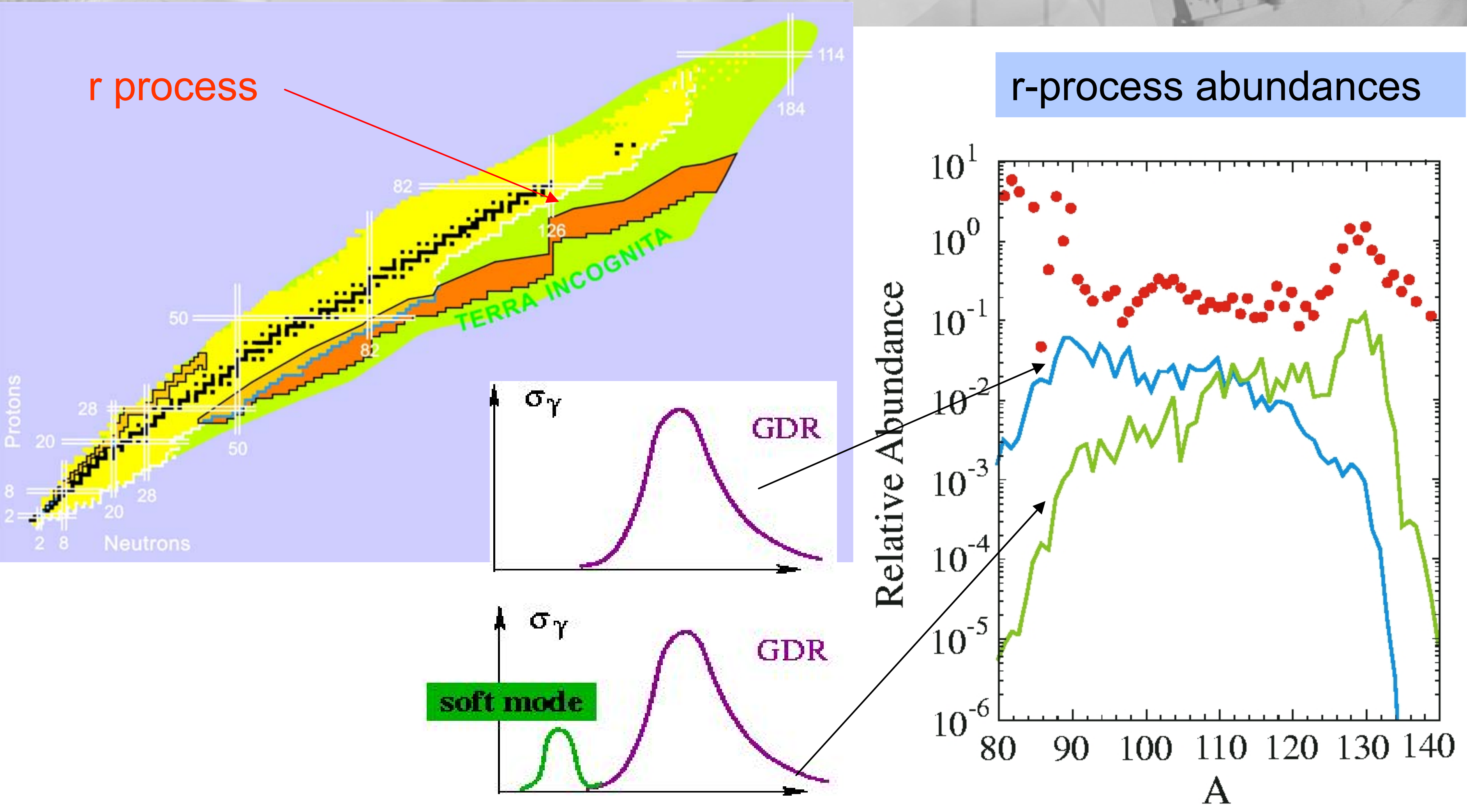
$$\times \sum_m |\langle \boldsymbol{q}|(Ze/A)rY_m^1|\phi_{n\ell j}(r)\rangle|^2.$$



Prediction: RMF
(N. Paar et al.)

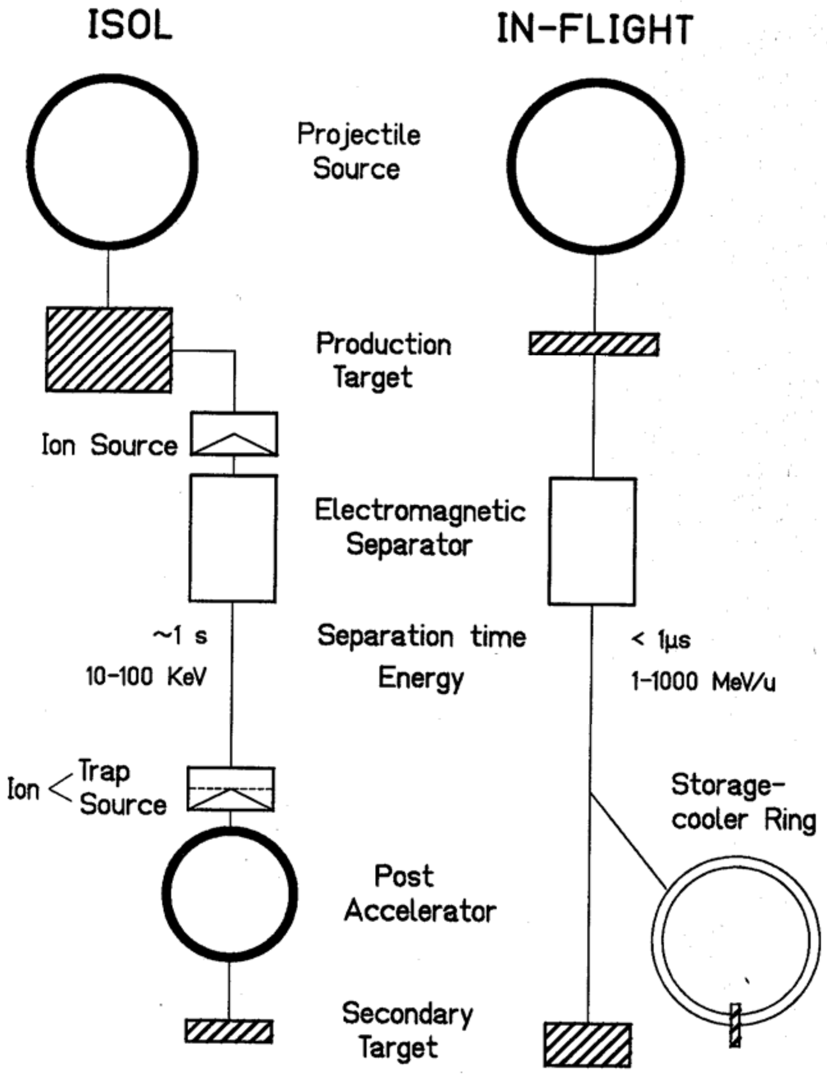


Astrophysical implications: r-process



S. Goriely, Phys. Lett. B 436 (1998) 10.
(schematic calculation)

Production of radioactive beams: Methods



H. Geissel, G. Münzenberg, K. Riisager, Annu. Rev. Nucl. Part. Sci. 45 (1995) 163

IN-FLIGHT:

relativistic heavy ions (50 MeV/u – 1 GeV/u)

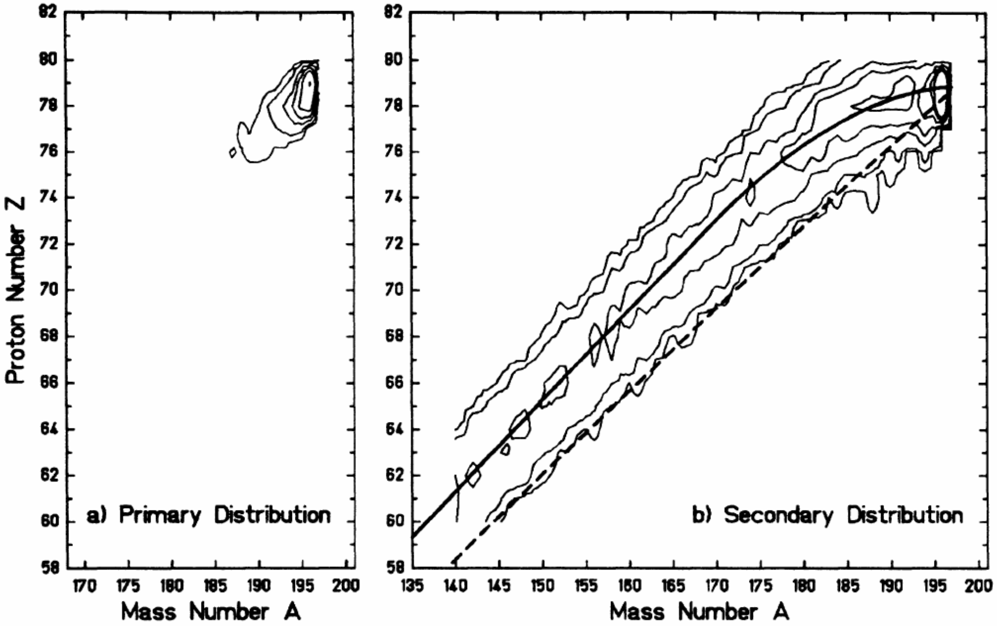
- fragmentation
- fission (elm. or nuclear induced)

ISOL:

- spallation (~1 GeV protons)
- fission: p-induced, fast neutrons (d beam), slow neutrons (reactor), photons (e^- beam)
- fusion/evaporation, multi-nucleon transfer

Fragmentation

Intra-nuclear cascade calculation
(K. Sümmerer et al., PRC 42 (1990) 2546



Empirical formula for production cross sections: EPAX

K. Sümmerer, B.Blank, PRC 61 (2000) 034607

Two-step process:

1) Abrasion of nucleons

→ pre-fragment: $\langle A/Z \rangle \sim (A/Z)_{proj}$

→ excitation energy

- geometrical overlap (Glauber model) + energy of created holes (Fermi gas, shell model)
- Intra-nuclear cascade (INC)

2) Ablation (Evaporation of nucleons)

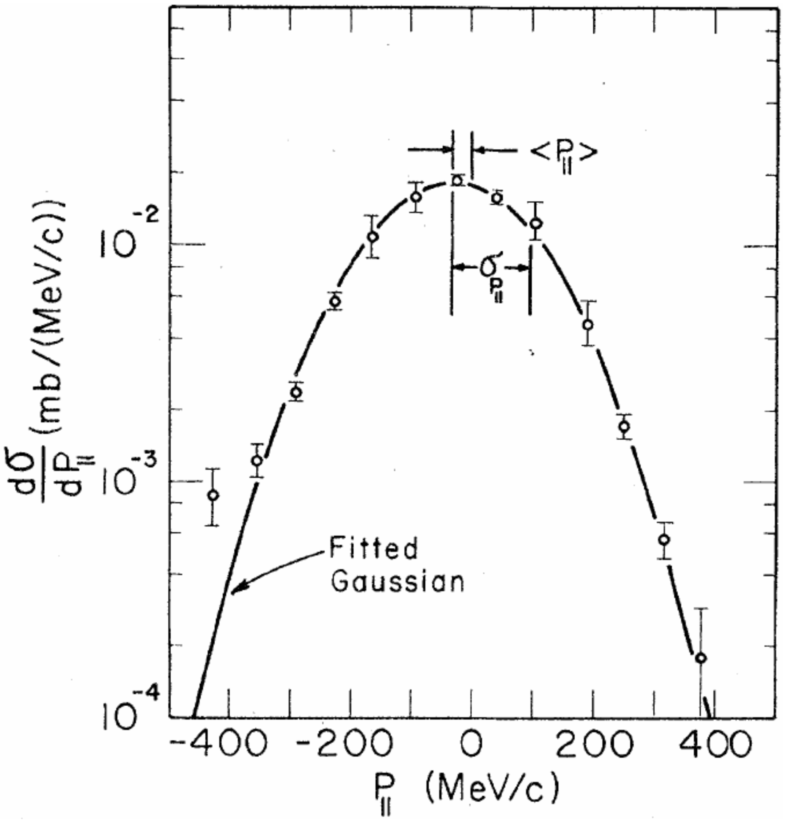
→ fragment: $\langle A/Z \rangle < (A/Z)_{proj}$

- statistical model (compound nucleus), also fission

(see, e.g., M.deJong et al., NPA 613 (1997) 435

Momentum distributions after fragmentation

2.1 GeV/u ^{12}C + Be → ^{10}Be



First experiments at the BEVALAC

D.E. Greiner et al., PRL 35 (1975) 152

$$\beta_{fragment} \approx \beta_{projectile}$$

momentum distributions gaussian

$$\sigma_{P||} \approx \sigma_{P\perp}$$

sudden approximation:

projectile rest frame: $\Sigma^{A} \mathbf{P}_n = 0$

momentum pre-fragment (PF): $\mathbf{P}_{Pf} = -\Sigma^{\Delta A} \mathbf{P}_n$

average nucleon momentum: $<P_n>=\sqrt{3/5}\, P_F$

Fermi momentum $P_F \approx 250$ MeV/c

Abrasion: $\sigma_P^2 = P_F^2/5\ \Delta A\ A_{Pf}/(A-1)$

A.S. Goldhaber (1974)

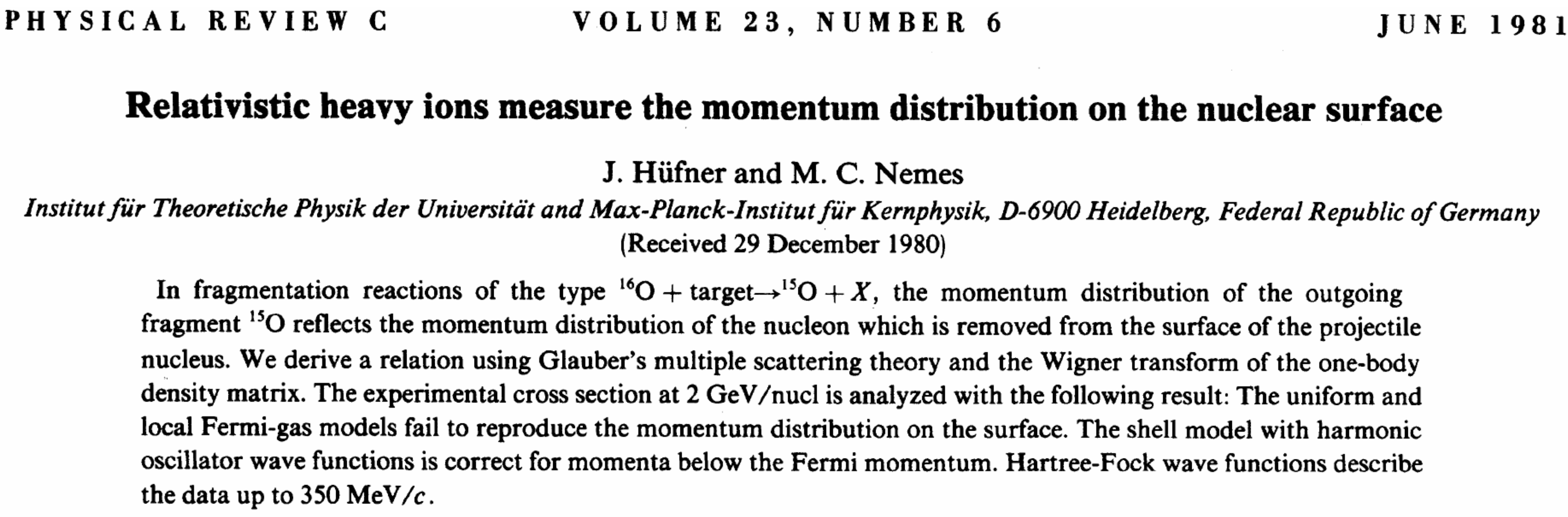
Taking into account evaporation:

A.Abul-Magd and J. Hüfner 1976

$$\sigma_{evaporation} < \sigma_{abrasion}$$

$$\Rightarrow \sigma_{total} < \sigma_{Goldhaber}$$

Momentum distributions



PHYSICAL REVIEW C VOLUME 23, NUMBER 6 JUNE 1981

Relativistic heavy ions measure the momentum distribution on the nuclear surface

J. Hüfner and M. C. Nemes
Institut für Theoretische Physik der Universität and Max-Planck-Institut für Kernphysik, D-6900 Heidelberg, Federal Republic of Germany

(Received 29 December 1980)

In fragmentation reactions of the type $^{16}O + \text{target} \rightarrow {}^{15}O + X$, the momentum distribution of the outgoing fragment ^{15}O reflects the momentum distribution of the nucleon which is removed from the surface of the projectile nucleus. We derive a relation using Glauber's multiple scattering theory and the Wigner transform of the one-body density matrix. The experimental cross section at 2 GeV/nucl is analyzed with the following result: The uniform and local Fermi-gas models fail to reproduce the momentum distribution on the surface. The shell model with harmonic oscillator wave functions is correct for momenta below the Fermi momentum. Hartree-Fock wave functions describe the data up to 350 MeV/*c*.

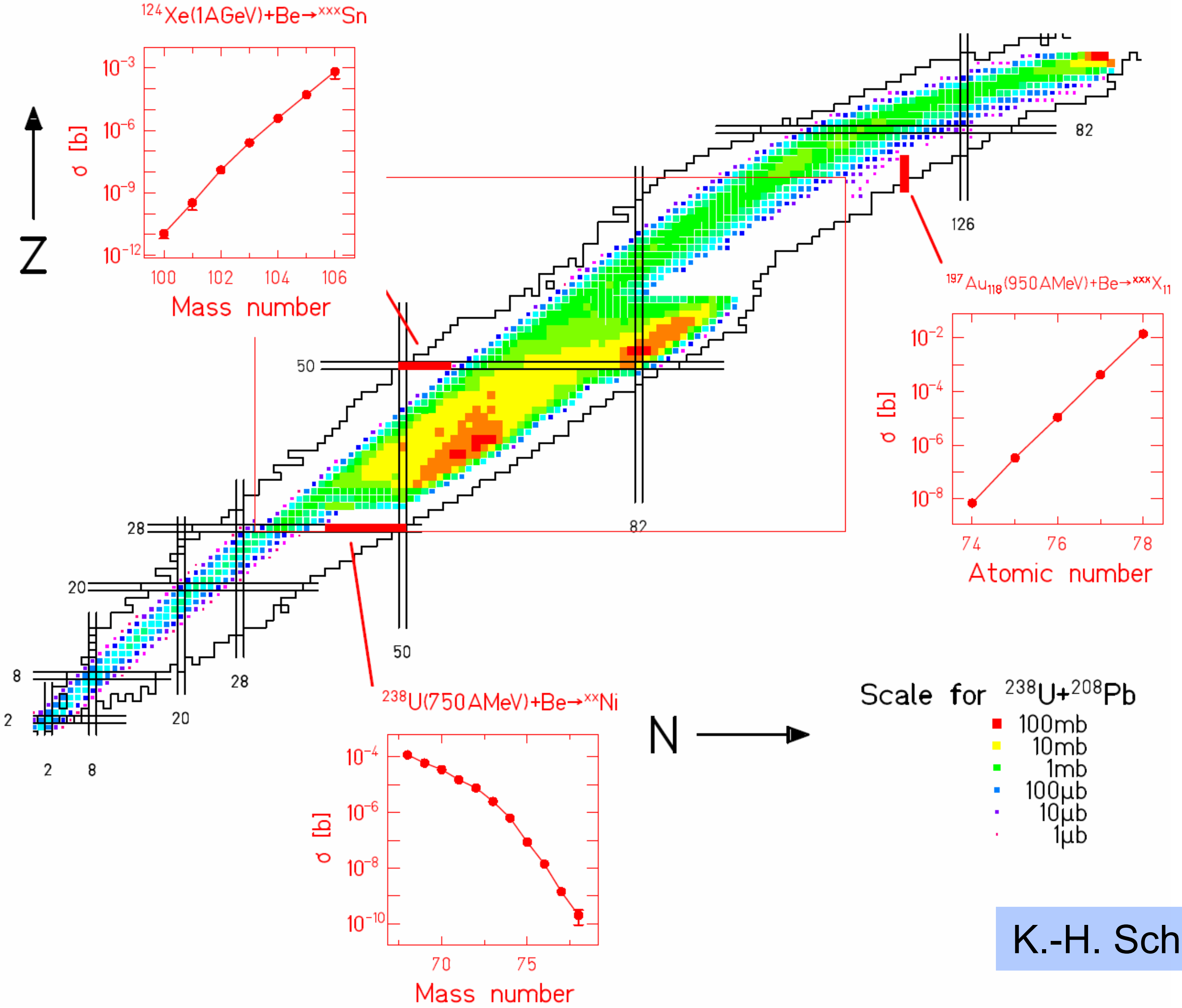
Application to radioactive beams (knockout reactions) for nuclear-structure studies

→ Measurement of the nucleon momentum distribution in the nucleus

→ Spatial extension of the wave function (Heisenberg)

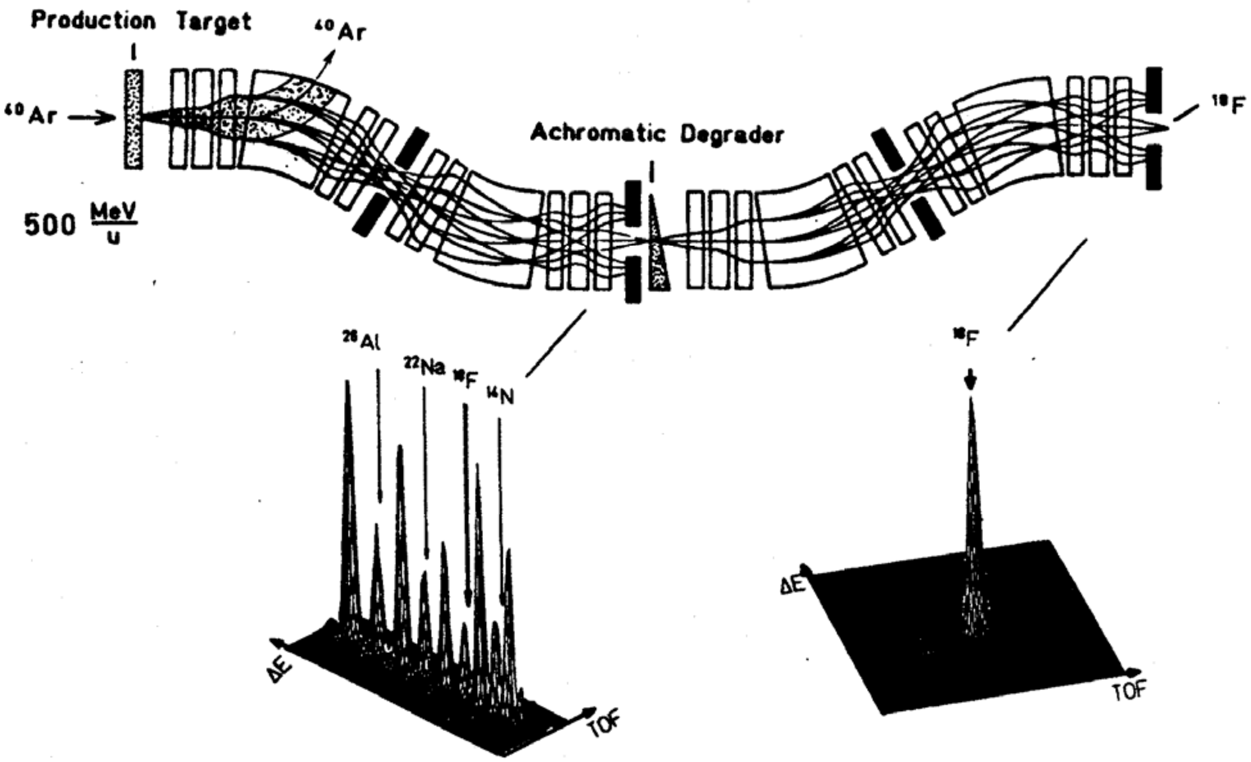
→ determination of the angular momentum of knocked-out nucleons

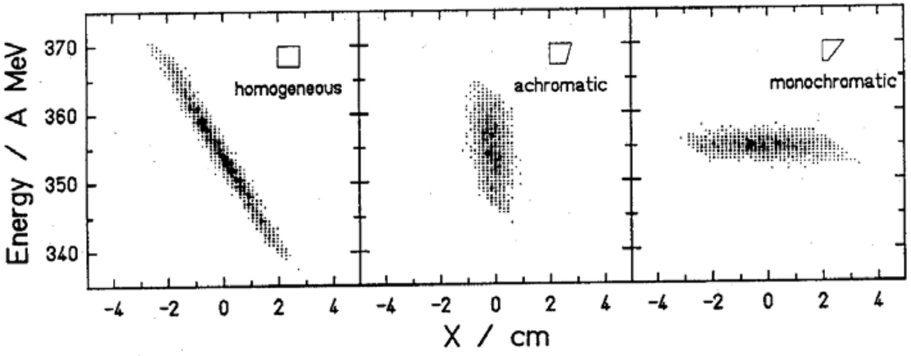
Production cross sections for fragmentation and fission



K.-H. Schmidt et al.

Separation of radioactive beams





Degrader as ion-optical element

$B\rho$ – ΔE – $B\rho$ Method

$B\rho \propto \beta\gamma\, A/Z$

$\Delta E \propto Z^2\, f(\beta)$

high beam energy
→ fully stripped ions

Measurement: x, ToF, ΔE

acceptance FRS@GSI:

±1% ($\Delta p/p$)

±13mrad (transversal)

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

Summary: Secondary Beams and High-Energy Scattering

$0.6 < v/c < 0.8$

Physics Aspects:

short interaction time ➔ sudden process
σ_{NN} lowest at ~ 300 MeV ➔ reduced re-scattering
low transverse momentum ➔ eikonal approximation

→ reaction dynamics and nuclear structure less entangled

Experimental Aspects:

Thick targets (g/cm^2) ➔ increased luminosity
Lorentz boost ➔ full solid angle
coverage . ➔ 100%
detection efficiency mixed secondary beams

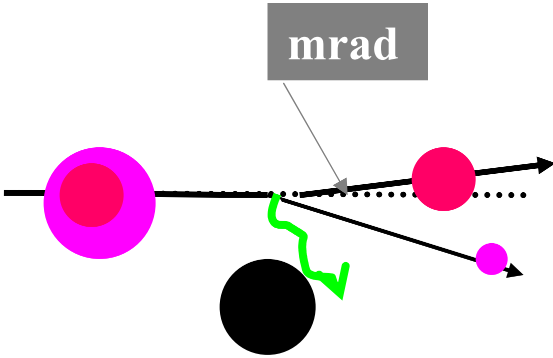
→ compensating low beam intensity (1 - 10000 s^{-1})

GSI: up to 1 GeV/A

Other Laboratories

(up to ~ 0.1 GeV/A):

GANIL / France
MSU / U.S.
RIKEN / Japan



for a recent review on reaction models, see
J. Al-Khalili and F. Nunes, J.Phys.G 29 (2003) R89

Summary: Physics of exotic nuclei and high-energy reactions

A broad physics programme

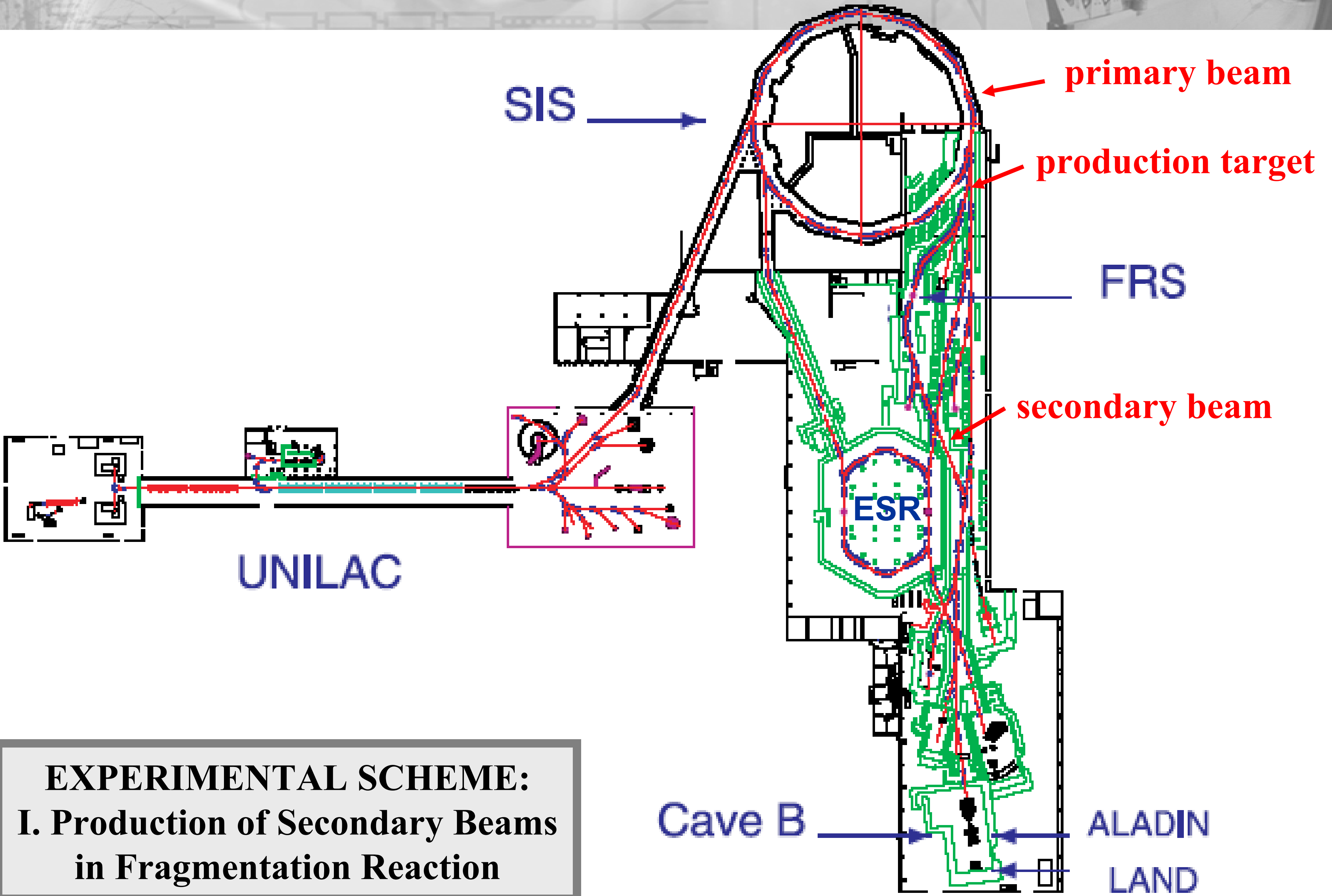
	Experiment
Nuclear radii, density distributions, halos and skins, nuclear equation of state	Total-absorption measurements, proton elastic scattering, knockout and momentum distributions, spin-dipole excitations
Shell structure far off stability, single-particle occupancies, spectral functions	Knockout reactions, quasi-free scattering, Coulomb breakup
Dipole response of exotic nuclei, giant dipole resonance and soft modes	Heavy-ion induced electromagnetic excitation
Nuclei beyond the neutron drip-line	Knockout reactions
Astrophysics	(γ,n) and (γ,p) cross sections (Coulomb breakup) Gamov-Teller transitions (charge-exchange)
Gamma spectroscopy	Knockout and fragmentation
Large-amplitude motion	Multifragmentation and fission
Reaction mechanisms/applications (hybrid reactors etc)	Spallation and fission

✔ Introduction: Physics, Experiments, Production

☛ **At and beyond the drip line: knockout reactions**

- Dipole excitations of neutron-rich nuclei
  - Coulomb breakup of halo nuclei
  - Giant and Pygmy collective excitations
- Future developments: Experimental Program at FAIR

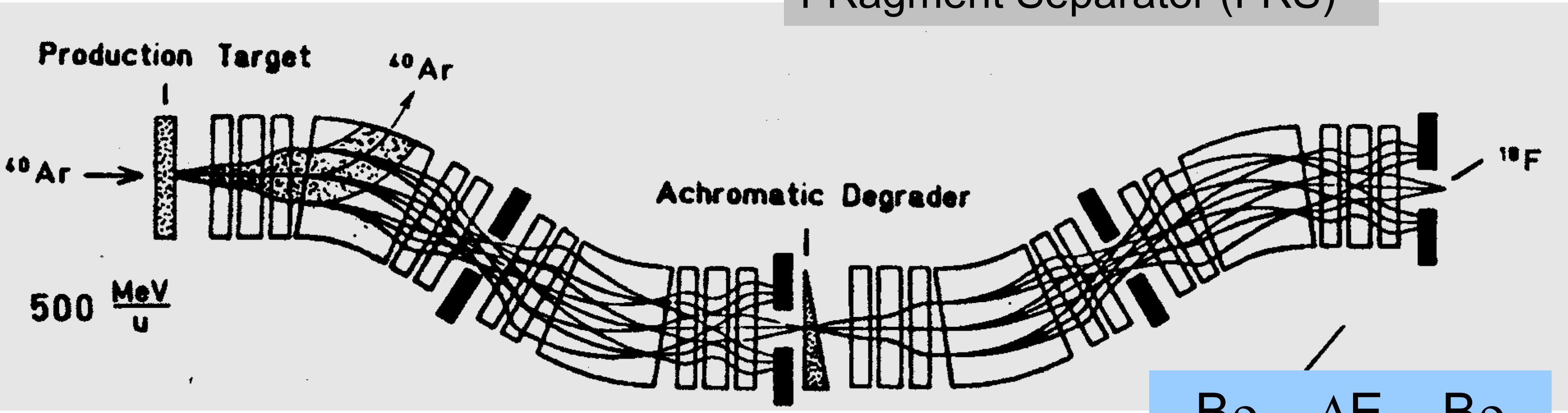
The GSI accelerator facilities



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

Experimental Scheme: II. Separation in FLIGHT

FRagment Separator (FRS)



Separation in Flight : v_{frag} ≈ v_{beam}

Transport efficiency ~ 50 % (fragmentation); $\Delta p/p$ ~ 2 %

Magnetic separation only:

<u>mixed beam</u> (Z/A ~ const.)

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

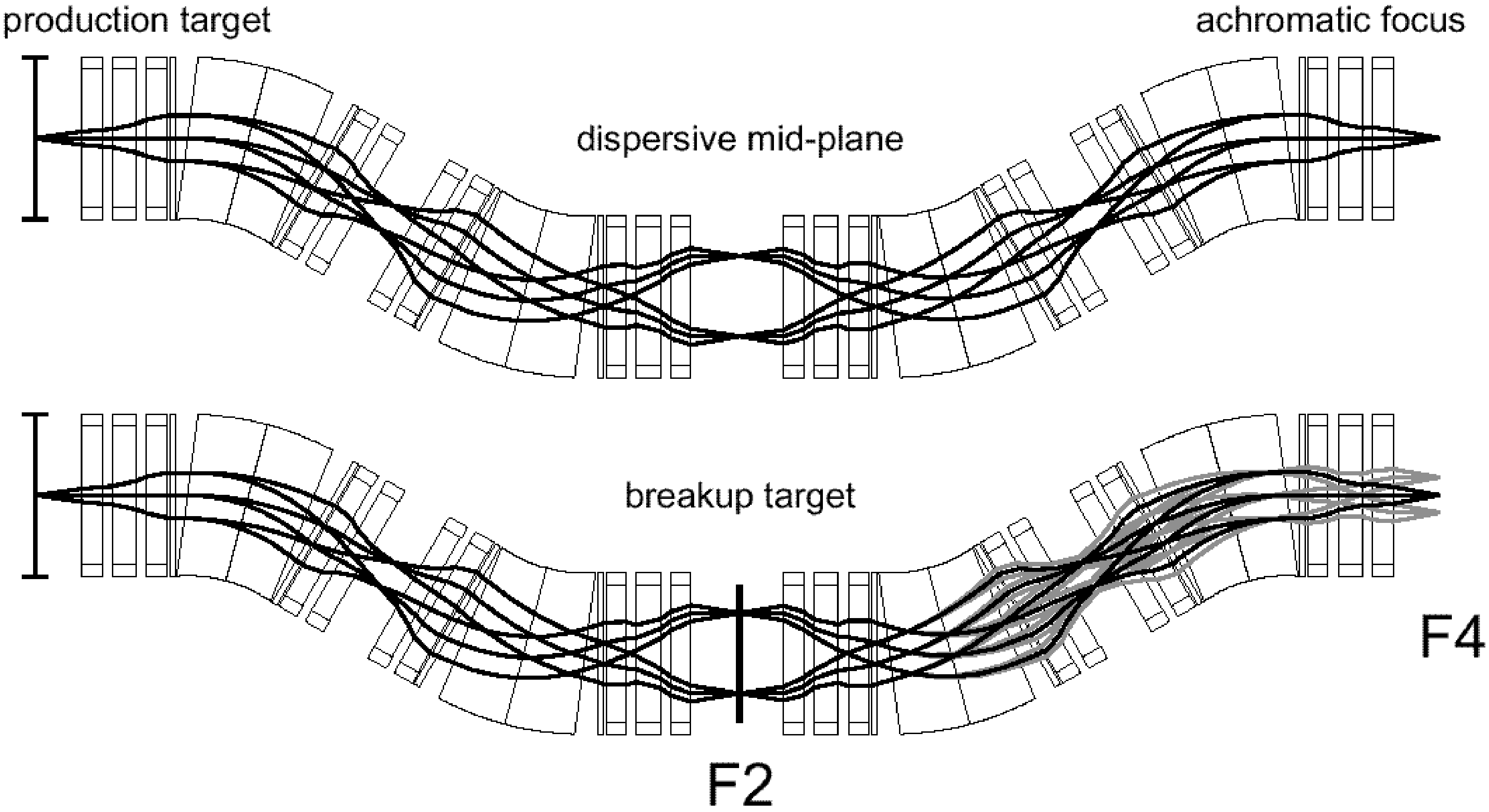
$B\rho \propto \beta\gamma\, A/Z$

$\Delta E \propto Z^2 f(\beta)$

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

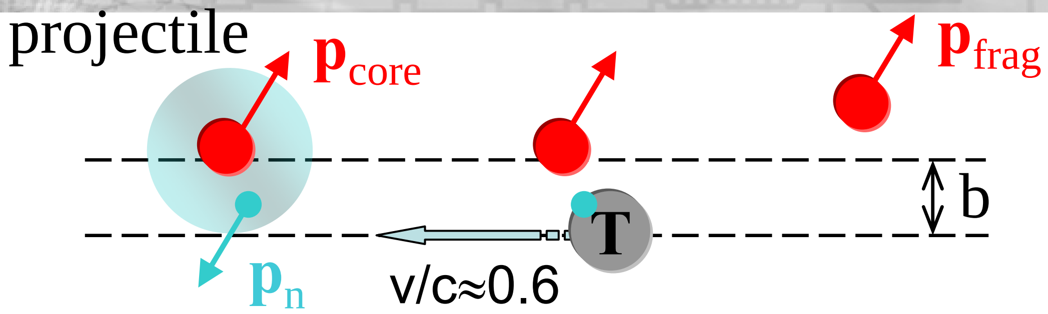
Measurement of momentum distributions

Dispersion matching: "Energy-loss mode"



Position (momentum) measurement at final focal plane
independent of initial momentum spread → high resolution

One-Nucleon Knockout: a Spectroscopic Tool



Sudden process

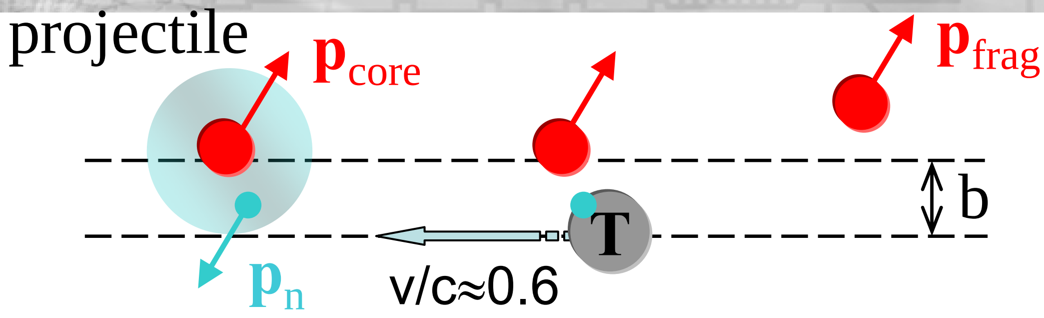
Reaction: $\Delta t \approx 10^{-22}$ s

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

⇒ $P_{frag} = -P_n$

⇒ measurement of wave function (at the surface: $b_c > r_c$)

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: $b_c>r_c$)**

Example:

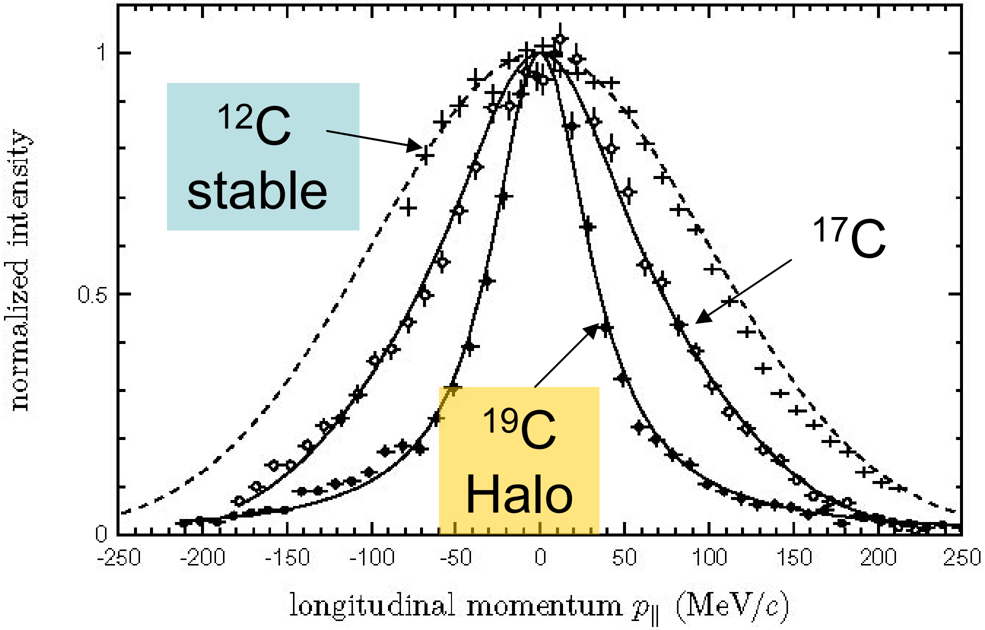
Carbon isotopes

$^{A}C + C \rightarrow {}^{A-1}C + x$

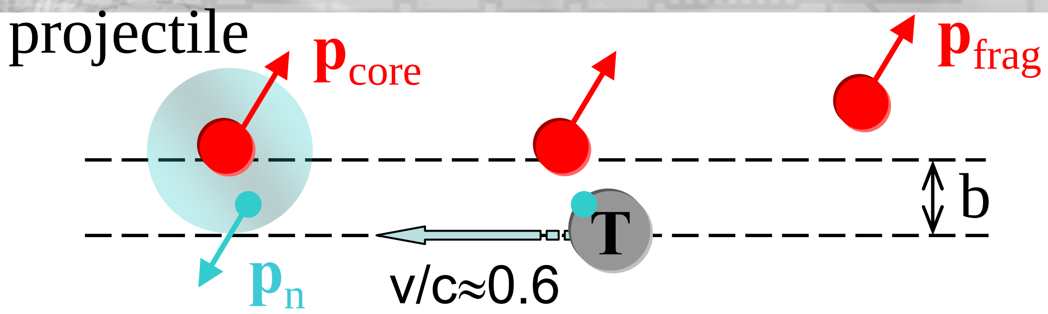
E ≈ 900 MeV/u

FRS@GSI

T. Baumann et al.



One-Nucleon Knockout: a Spectroscopic Tool



Sudden process

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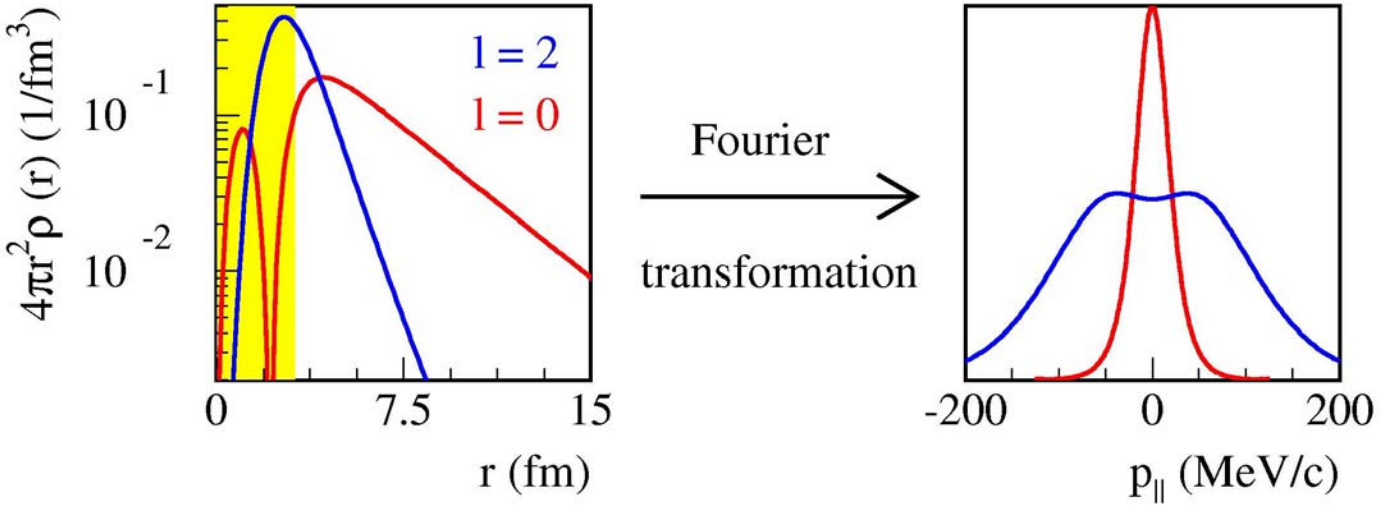
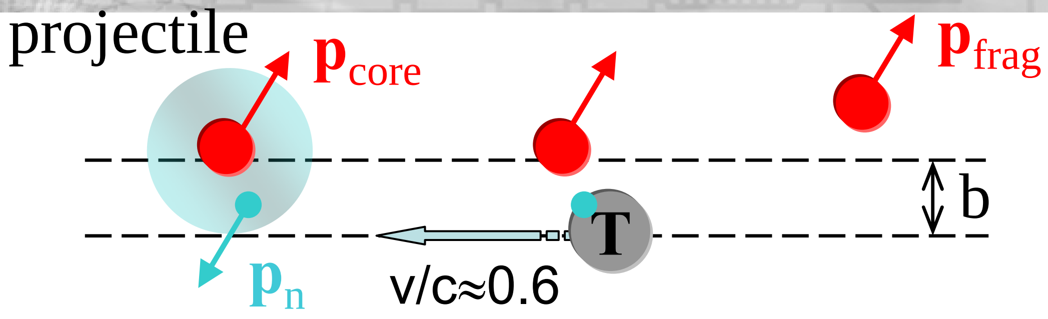


Extended Wavefunction

Narrow Momentum Distribution

One-Nucleon Knockout: a Spectroscopic Tool



Sudden process

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

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

⇒ $P_{frag} = -P_n$

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

Measurement	Observable
Momentum distribution	⇒ *l*-value of removed nucleon
γ-ray coincidence	⇒ identification of core-state
invariant mass (unbound states)	
Cross section	⇒ spectroscopic factor

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

Eikonal calculation

Single-particle cross sections

$$\sigma_{sp}(J^\pi) = \sigma_{sp}^{knockout} + \sigma_{sp}^{diffraction}$$

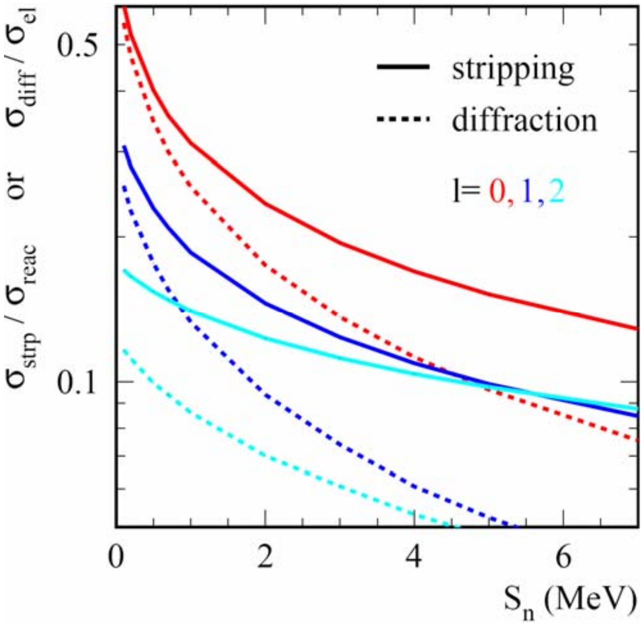
Eikonal approximation:

$$\sigma_{sp}^{knockout}(J^\pi) = \int d^2b \int d^3r \ |\Phi_{l,S_n}(\mathbf{r})|^2 \ \underset{\substack{\nearrow \\ \text{core survival} \\ \text{'shadowing'}}}{S_c^2(\mathbf{b_c})} \ \underset{\substack{\uparrow \\ \text{reaction} \\ n\,+\,\text{target}}}{(1 - S_n^2(\mathbf{b_n}))}$$

- $\Phi_{l,S_n}(\mathbf{r})$ is calculated for a Woods-Saxon Potential
- S_c, S_n are calculated using target and core density distributions
  + free NN cross sections + energy dep. ratio of imaginary to real part

→ no free parameters

One-neutron removal reaction (nuclear breakup)



Reaction mechanisms:

- knockout (stripping)
- inelastic scattering (diffraction)

cross section dominated by knockout for

- high beam energies
- non-halo states

$$p_{stripping} = < S_c^2(\mathbf{b_c})[1 - S_n^2(\mathbf{b_n})] >$$

$$p_{inelastic} = < [1 - S_c(\mathbf{b_c})S_n(\mathbf{b_n})]^2 > - < 1 - S_c(\mathbf{b_c})S_n(\mathbf{b_n}) >^2$$

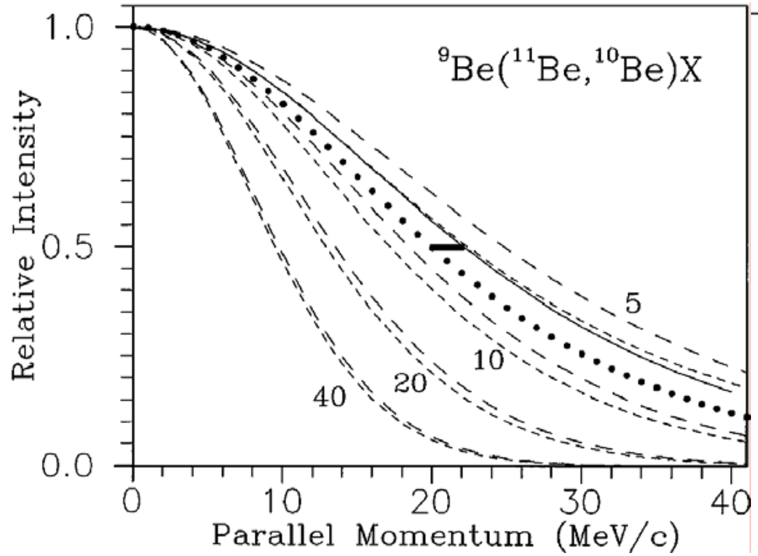
<u>no-recoil limit:</u> $A_c >> 1, \mathbf{b_c} = \mathbf{b}$

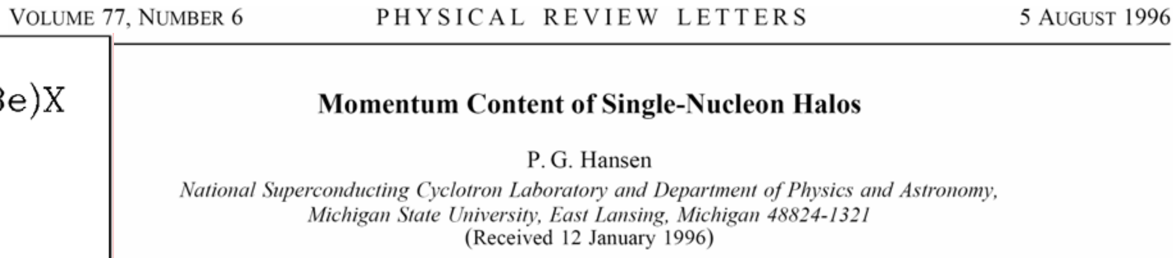
$$p_{diffraction} = S_c^2 < [1 - S_n(\mathbf{b_n})]^2 > - S_c^2 < 1 - S_n(\mathbf{b_n}) >^2$$

elastic scattering of neutron

elastic scattering of projectile

Momentum distributions and reaction mechanism





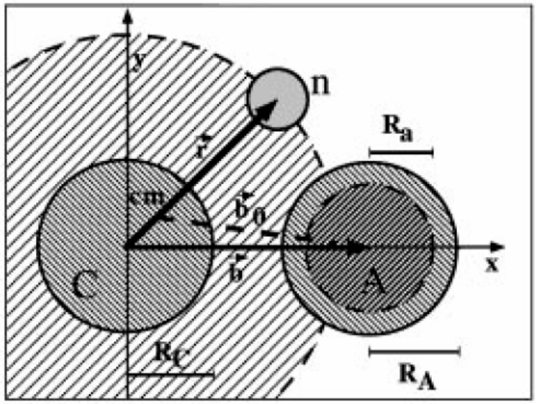
VOLUME 77, NUMBER 6 PHYSICAL REVIEW LETTERS 5 AUGUST 1996

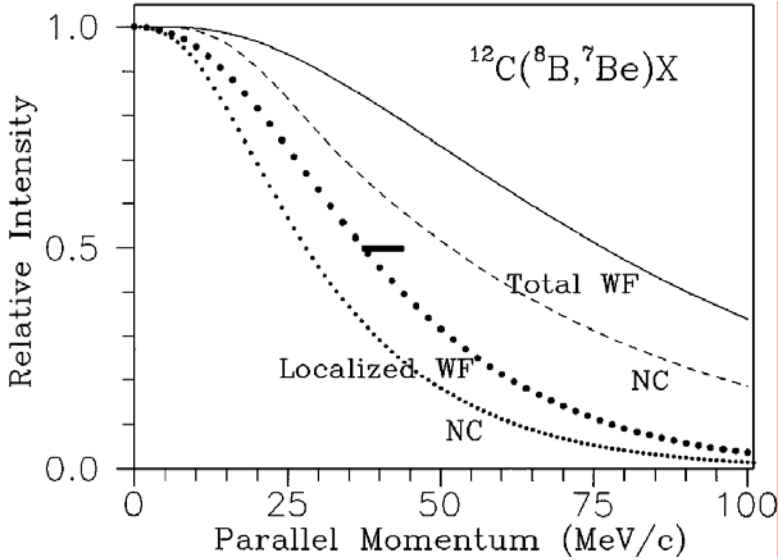
Momentum Content of Single-Nucleon Halos

P. G. Hansen

National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy,
Michigan State University, East Lansing, Michigan 48824-1321

(Received 12 January 1996)





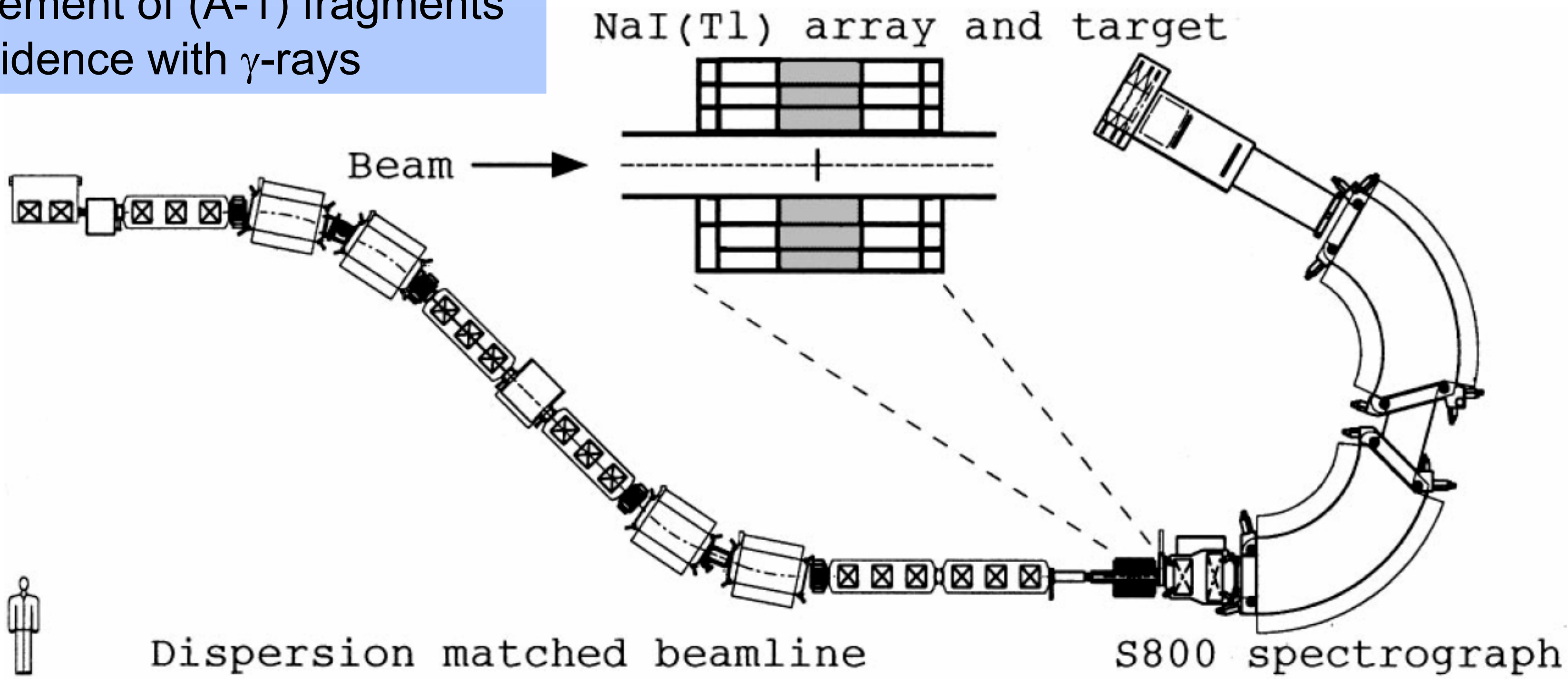
reaction samples only the surface of the nucleus

→ momentum distributions are more narrow than the full Fourier transform

effect less pronounced for well developed halos

Knockout reactions as spectroscopic tool: Setup at the NSCL@MSU

Measurement of (A-1) fragments in coincidence with γ-rays



momentum resolution for recoil: $\Delta p/p \sim 2.5 \times 10^{-4}$ acceptance ~ ±2.5%

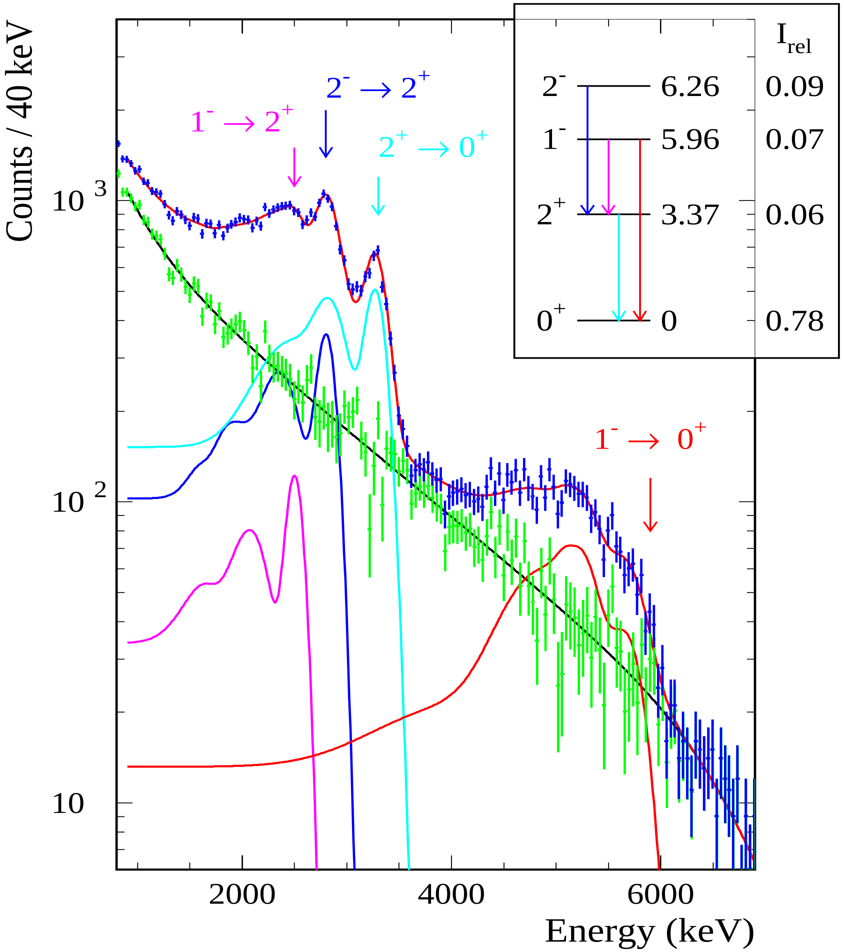
Reviews: P.G. Hansen, B.M. Sherrill, NPA 693 (2001) 133

P.G. Hansen, J.A. Tostevin, Annu. Rev. Nucl. Part. Sci 53 (2003) 219

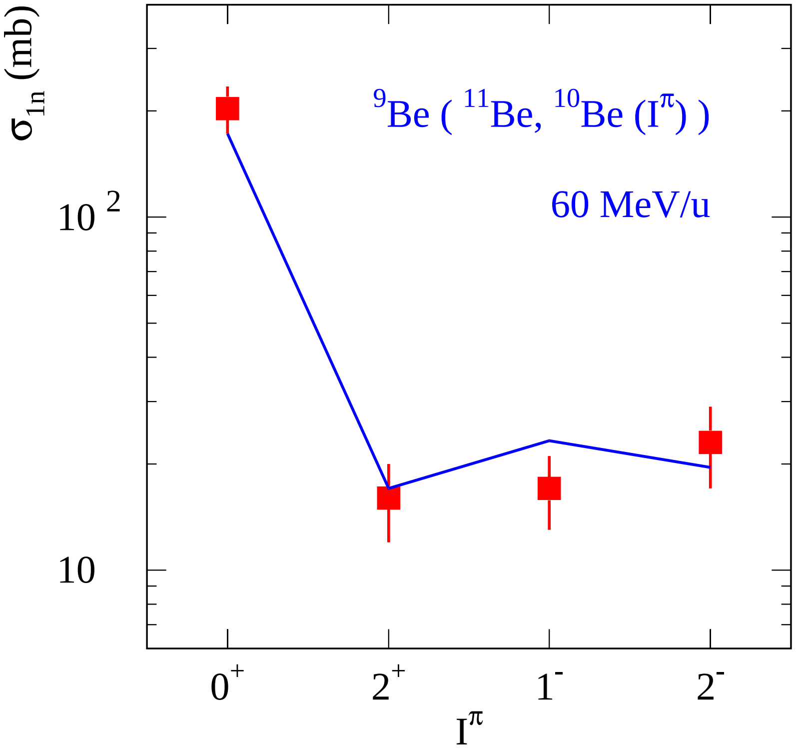
Neutron removal from individual single-particle states: $^{11}\text{Be} \rightarrow {}^{10}\text{Be}\ (I^\pi) + \gamma + X$

γ-ray coincidences

60 MeV/u $^{11}\text{Be} + \text{Be} \rightarrow {}^{10}\text{Be} + \gamma + X$



Partial cross sections



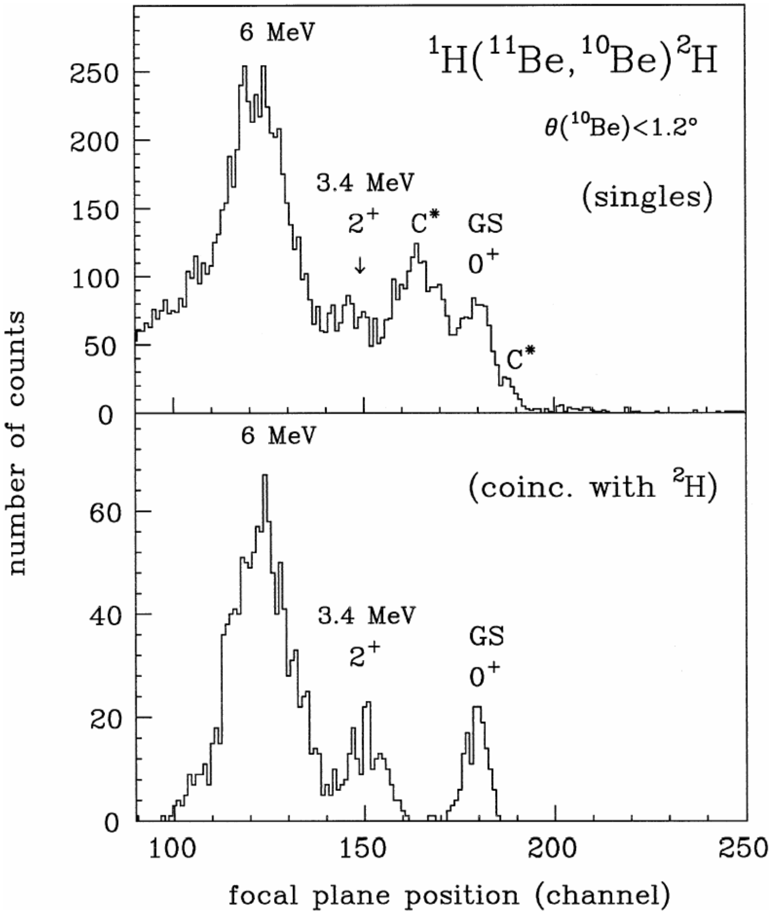
Spectroscopic factors

$S(0^+) \approx 0.8$

$S(2^+) \approx 0.2$

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

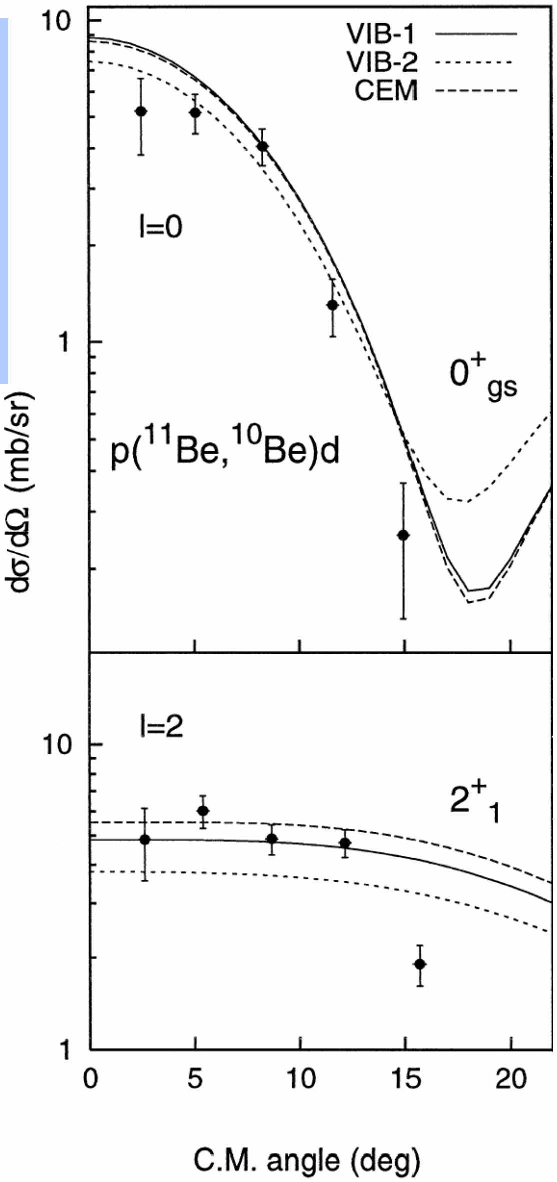
Comparison to transfer reactions



Transfer reaction in inverse kinematics:

GANIL, 35 MeV/u ^{11}Be

S. Fortier et al.,
PLB 461 (1999) 22



deduced spectroscopic factors in agreement with knockout reaction

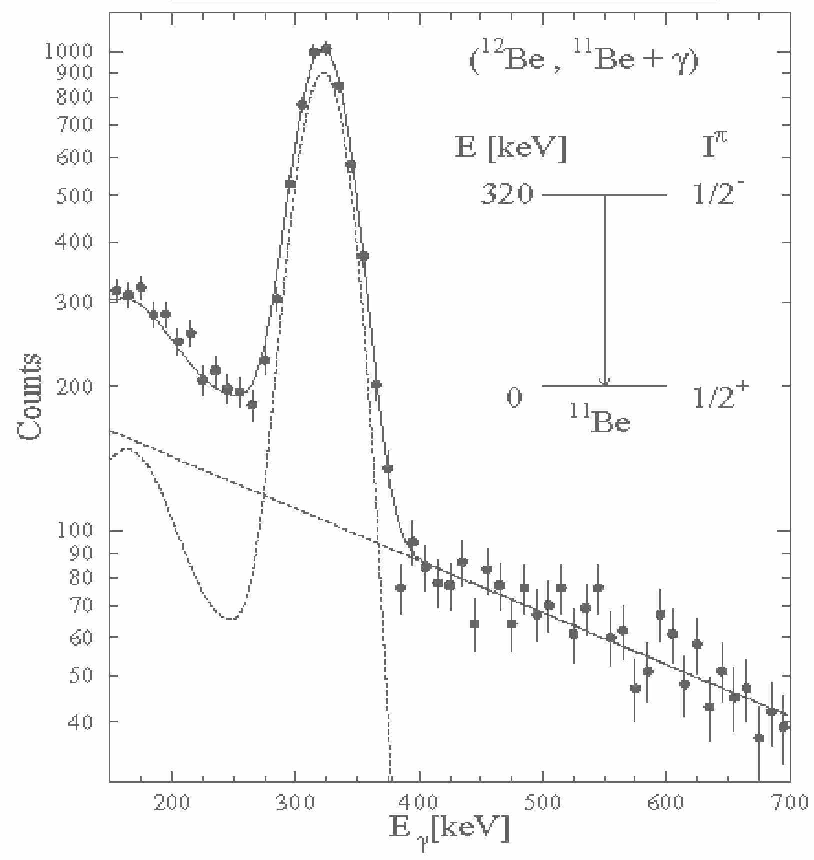
E_x (MeV)	J^π	SE-1 S_{exp}	VIB-1 S_{exp}	VIB-1 S_{th}	SE-2 S_{exp}	VIB-2 S_{exp}	VIB-2 S_{th}
0	0^+	0.66	0.67	0.84	0.79	0.79	0.84
3.368	2^+	0.28	0.17	0.16	0.38	0.22	0.16

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

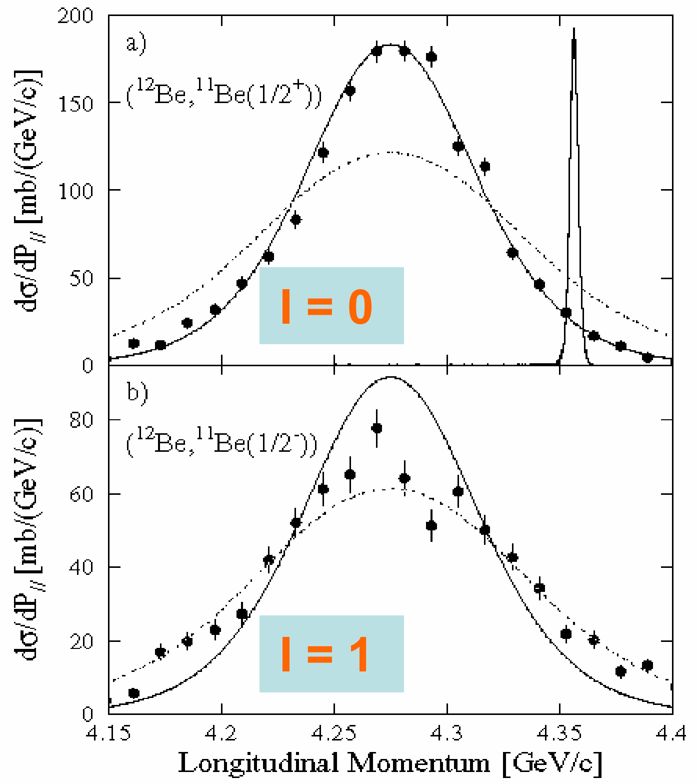
One-neutron removal reaction:

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

γ-ray coincidences



Momentum distributions

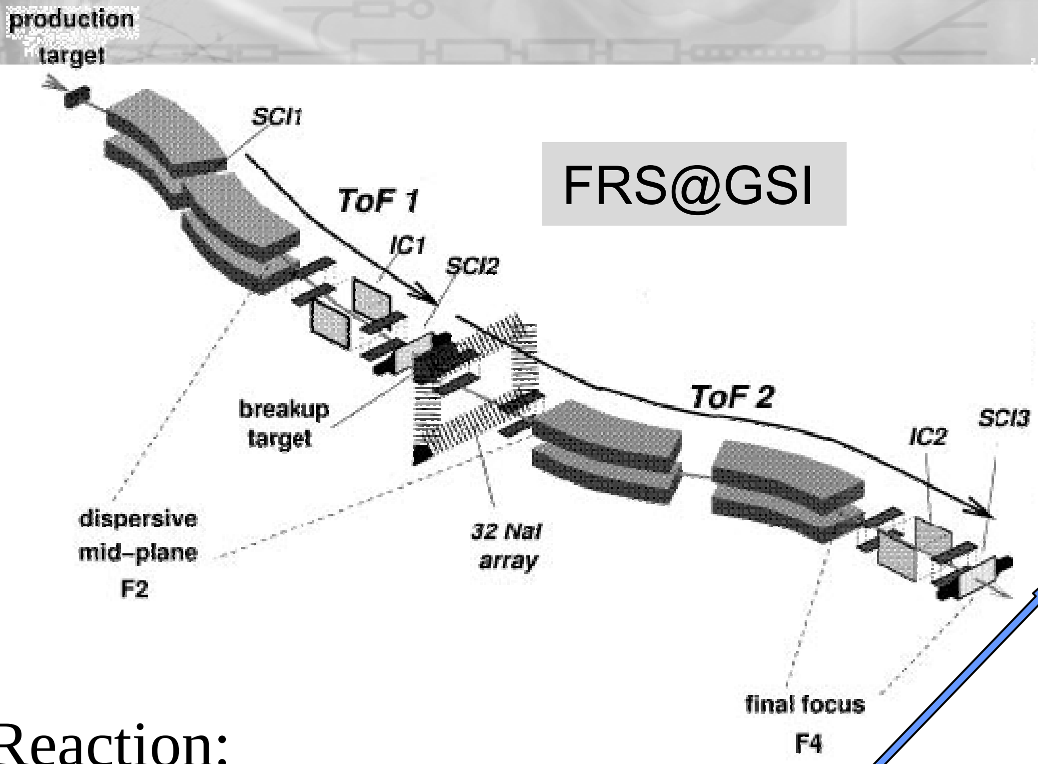


⇒ Mixed configurations

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

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

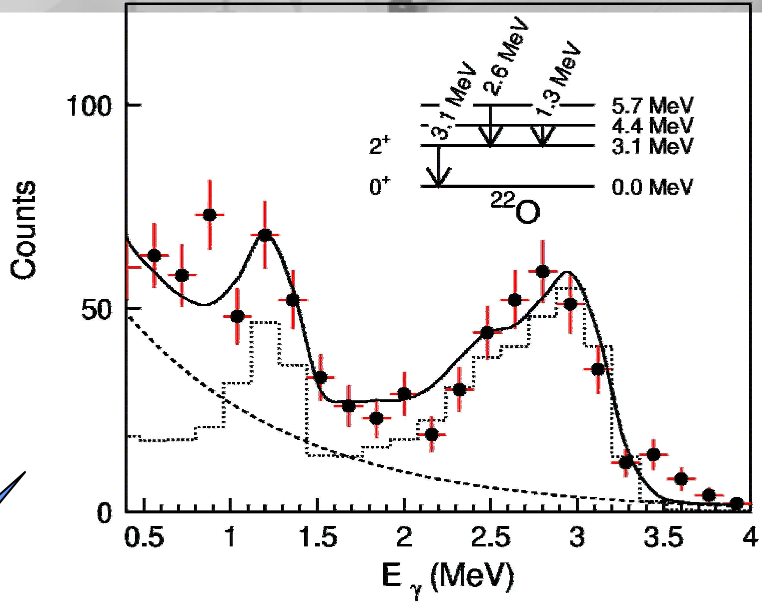
^{23}O: the heaviest halo nucleus?



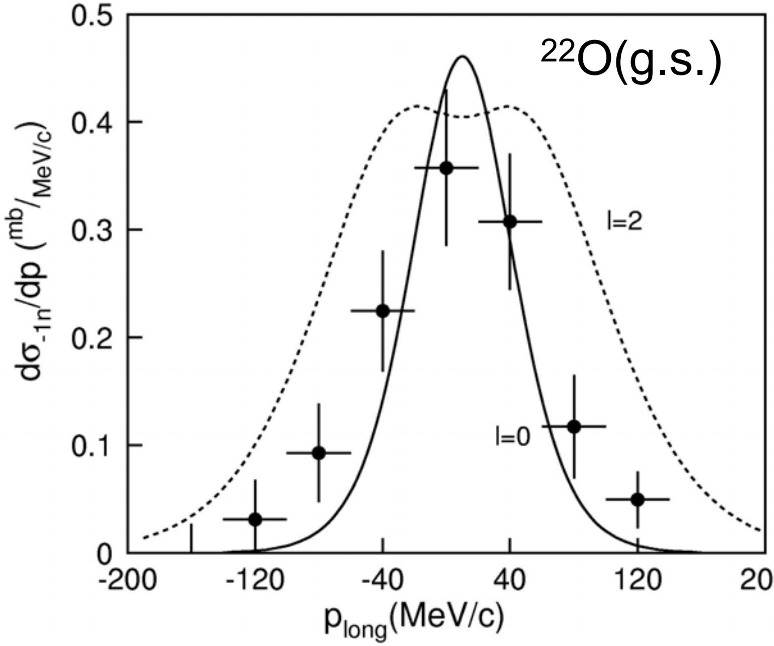
FRS@GSI

Reaction:

^{23}O (938 MeV/u) + C $\rightarrow$ ^{22}O + γ + x



Momentum distribution



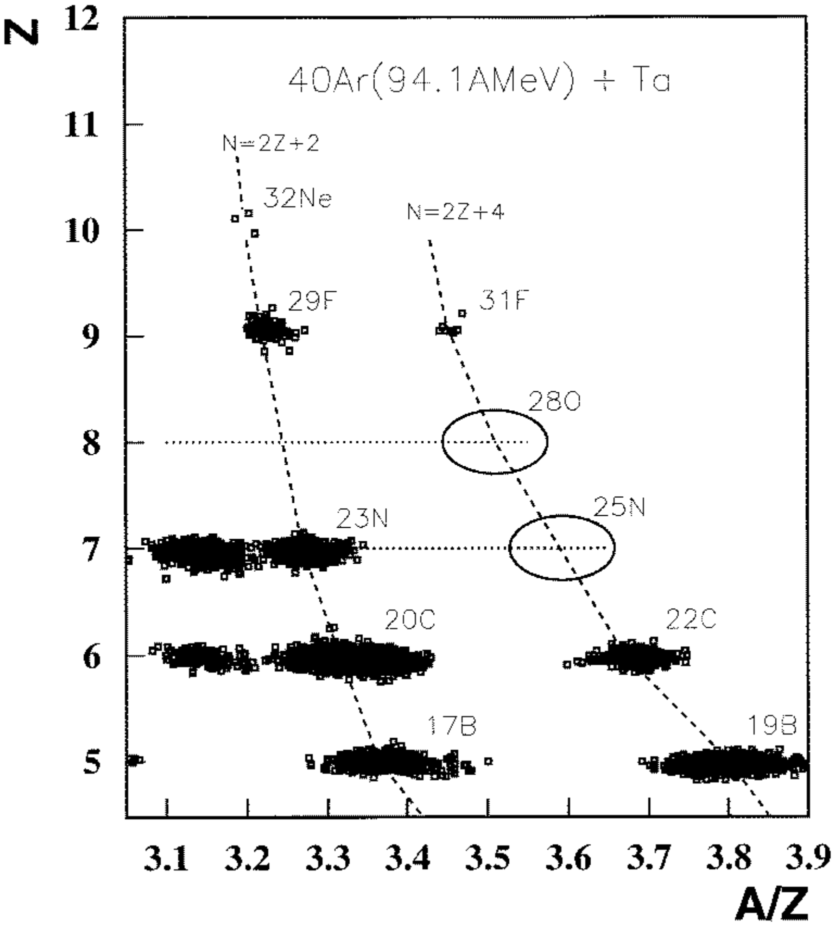
$\Rightarrow$ $I^{\pi} = 1/2^{+}$

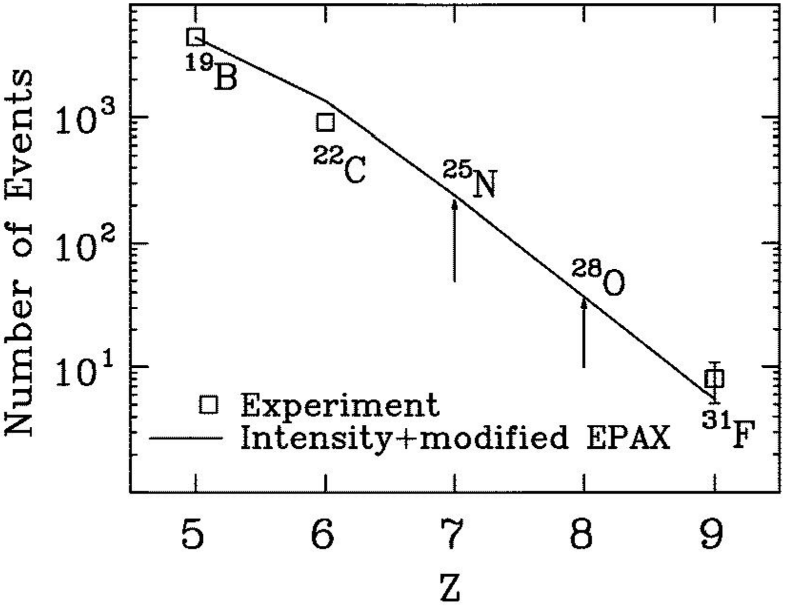
$\Rightarrow S(\nu_s \otimes {}^{22}O(0^+)) \approx 0.9(2)$

D. Cortina-Gil et al., Phys. Rev. Lett. 93 (2004) 062501

The N=20 (closed shell?) nucleus ^{28}O is unbound !

Experiment at RIKEN:





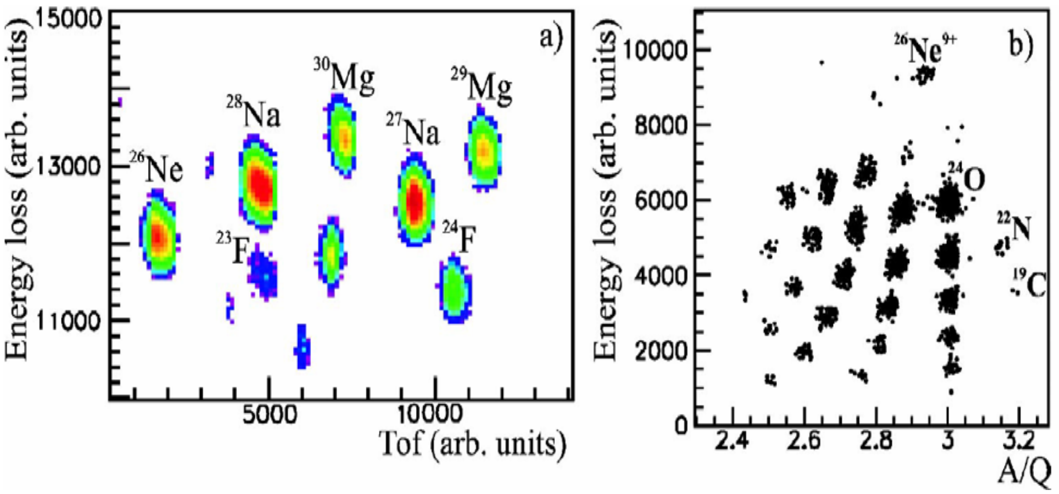
Location of the Neutron drip line only known up to Z = 8:

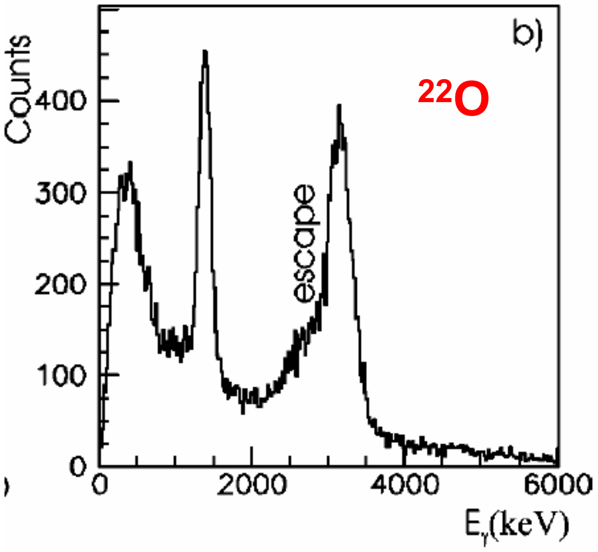
for Z = 8 → $N_{max} = 16$

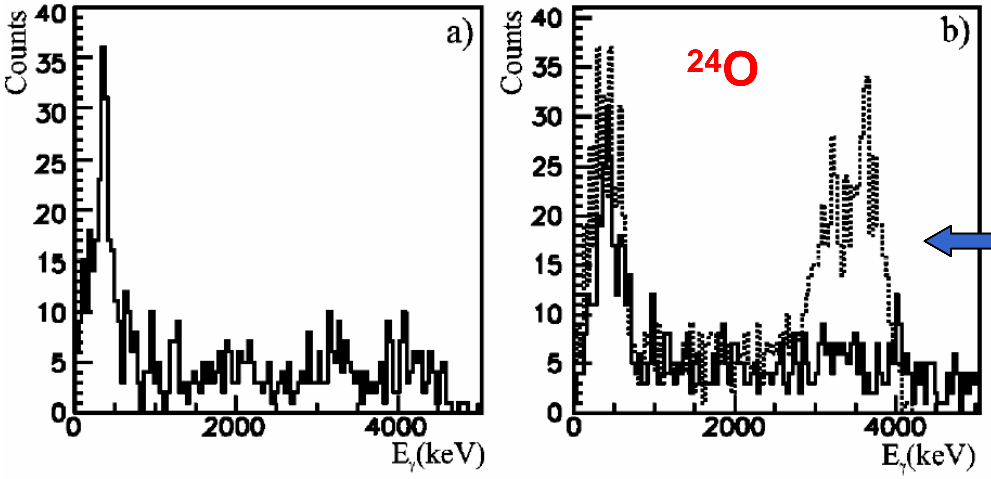
for Z = 9 → $N_{max} \geq 22$

H. Sakurai et al., Phys. Lett. B 448 (1999) 180

Secondary fragmentation plus γ spectroscopy







no 2^+ state observed

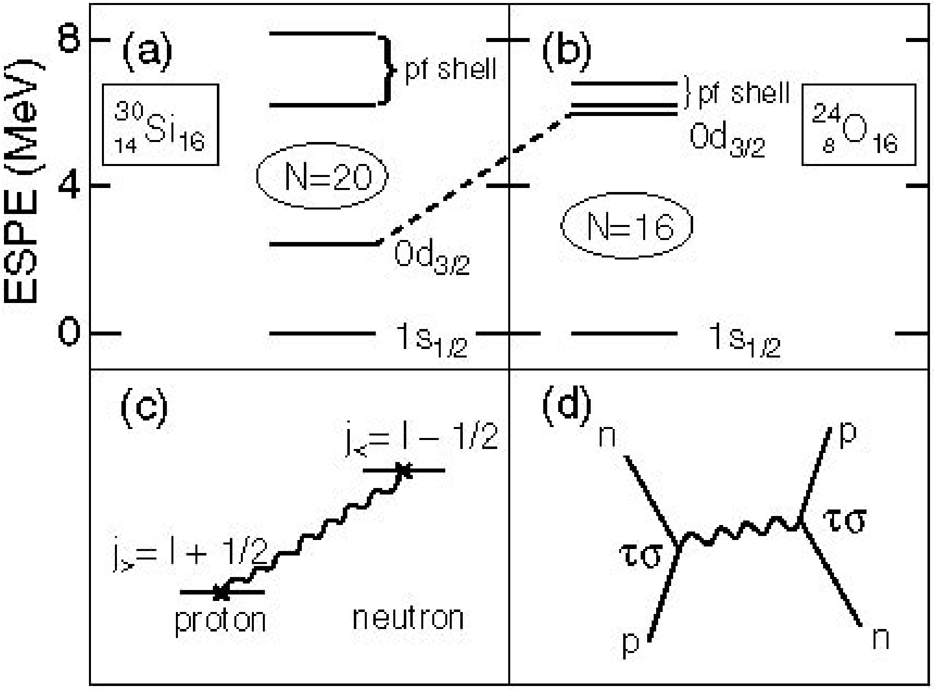
→ energy above threshold

M. Stanoiu, Phys. Rev. C **69** (2004) 034312

New magic number N=16

N=20 shell gap vanishes

New shell closure at N=16



All experiments consistently suggest a

vanishing of the N=20 shell gap (^{28}O unbound) and the

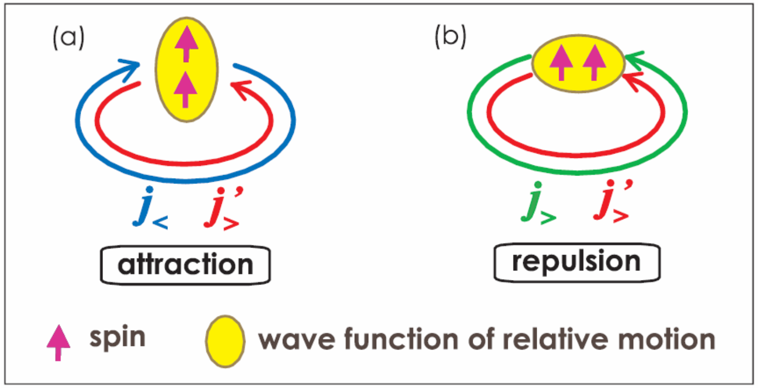
appearance of a shell closure for N=16 (large spectroscopic factor, high-lying 2^+ state)

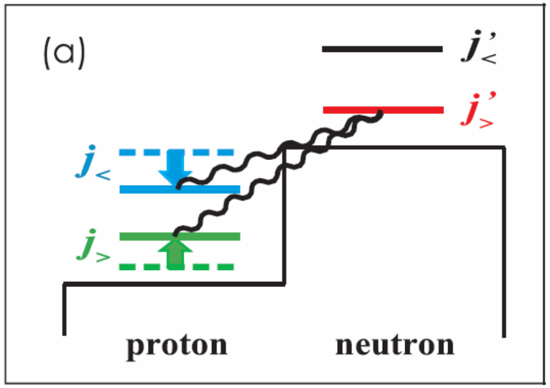
for the neutron-rich oxygen isotopes

Z=14 → Z=8

Removing $0d_{5/2}$ protons

→ less binding for $0d_{3/2}$ neutrons





T. Otsuka et al.,
PRL87(2001)082502
PRL95(2005)232502

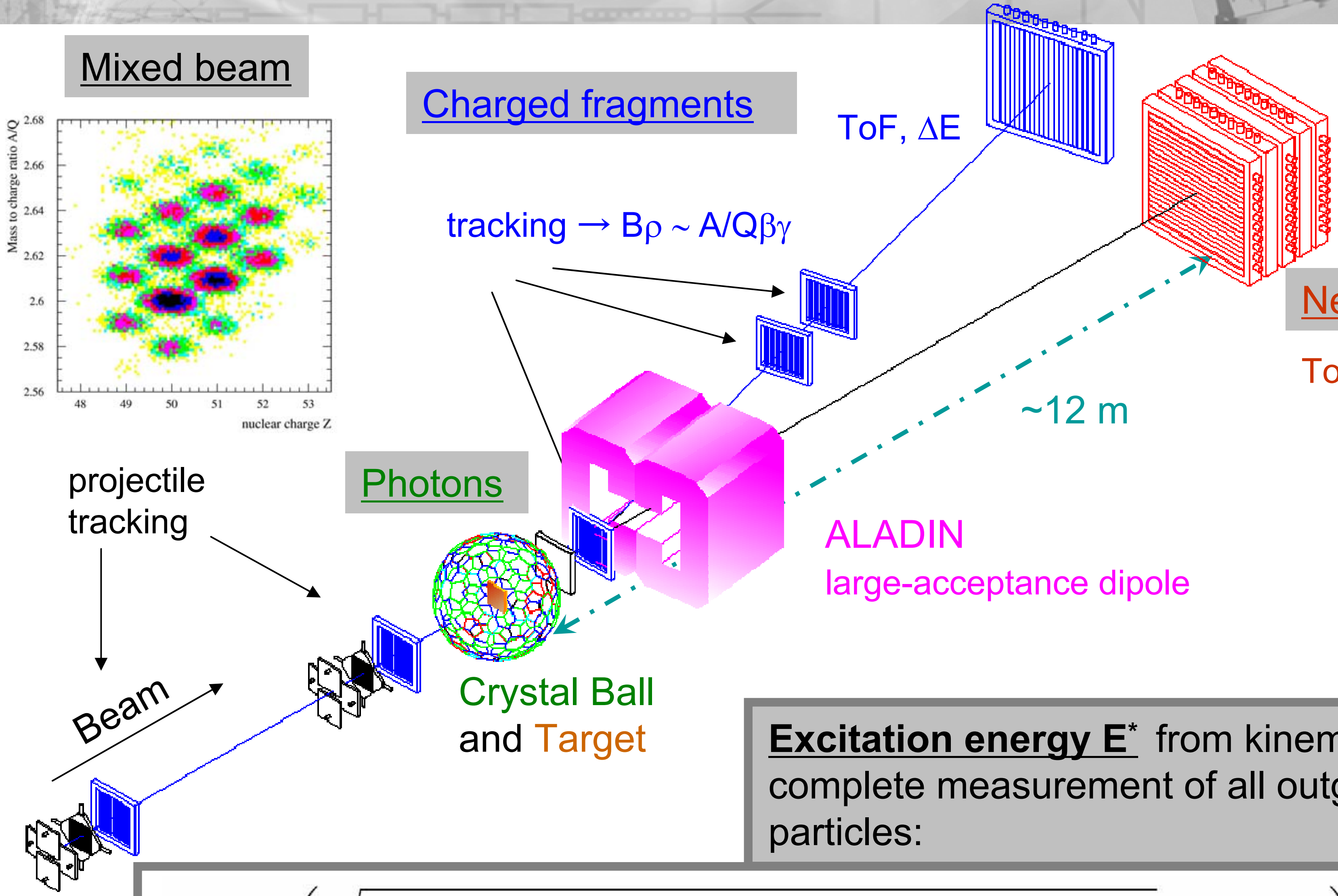
✔ Introduction: Physics, Experiments, Production

☛ **At and beyond the drip line: knockout reactions**

2) Knockout to unbound states

- Dipole excitations of neutron-rich nuclei
  - Coulomb breakup of halo nuclei
  - Giant and Pygmy collective excitations
- Future developments: Experimental Program at FAIR

Experimental Scheme: The LAND reaction setup @GSI



Mixed beam

Charged fragments

ToF, ΔE

tracking → Bρ ~ A/Qβγ

LAND

Neutrons

ToF, x, y, z

~12 m

projectile tracking

Photons

ALADIN

large-acceptance dipole

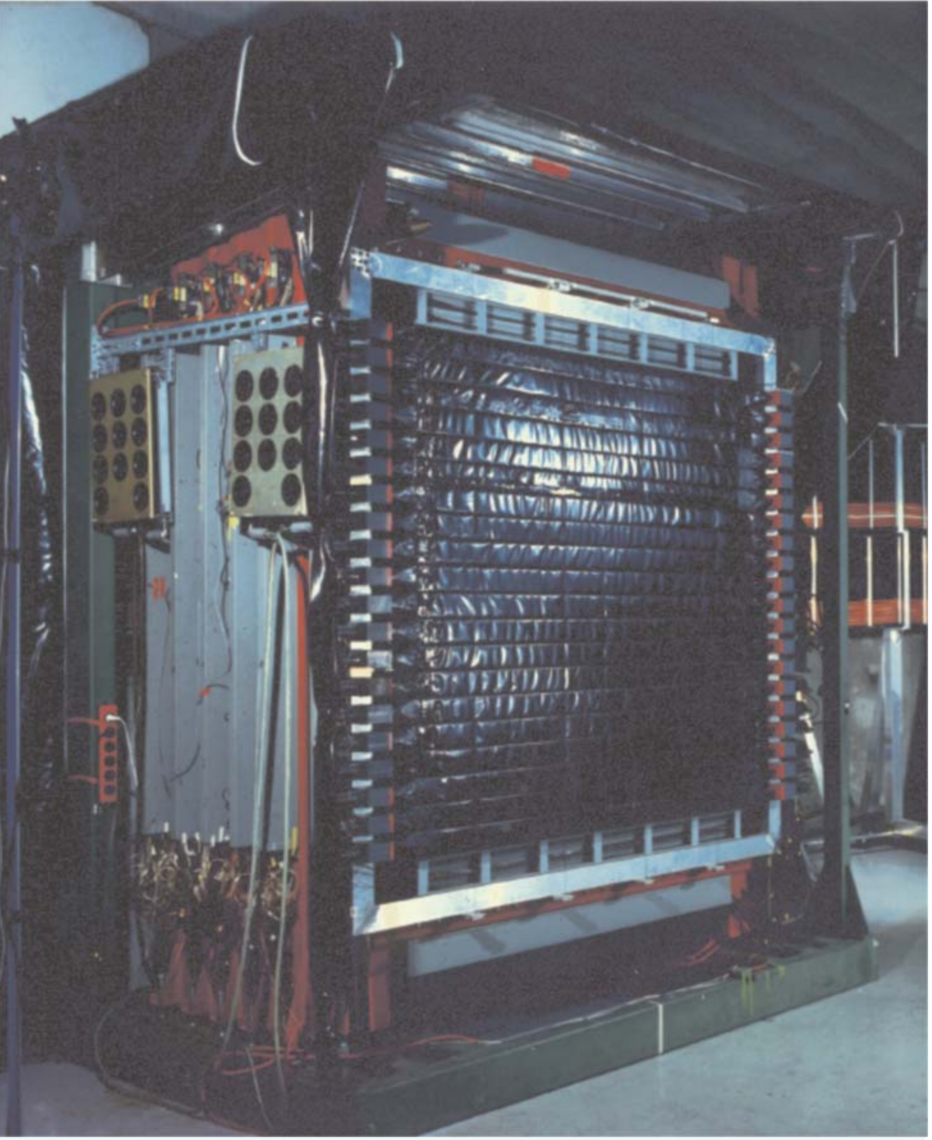
Beam

Crystal Ball and Target

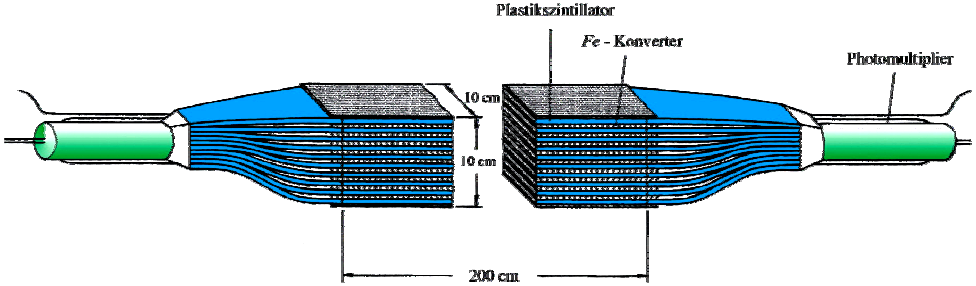
Excitation energy E* from kinematically complete measurement of all outgoing particles:

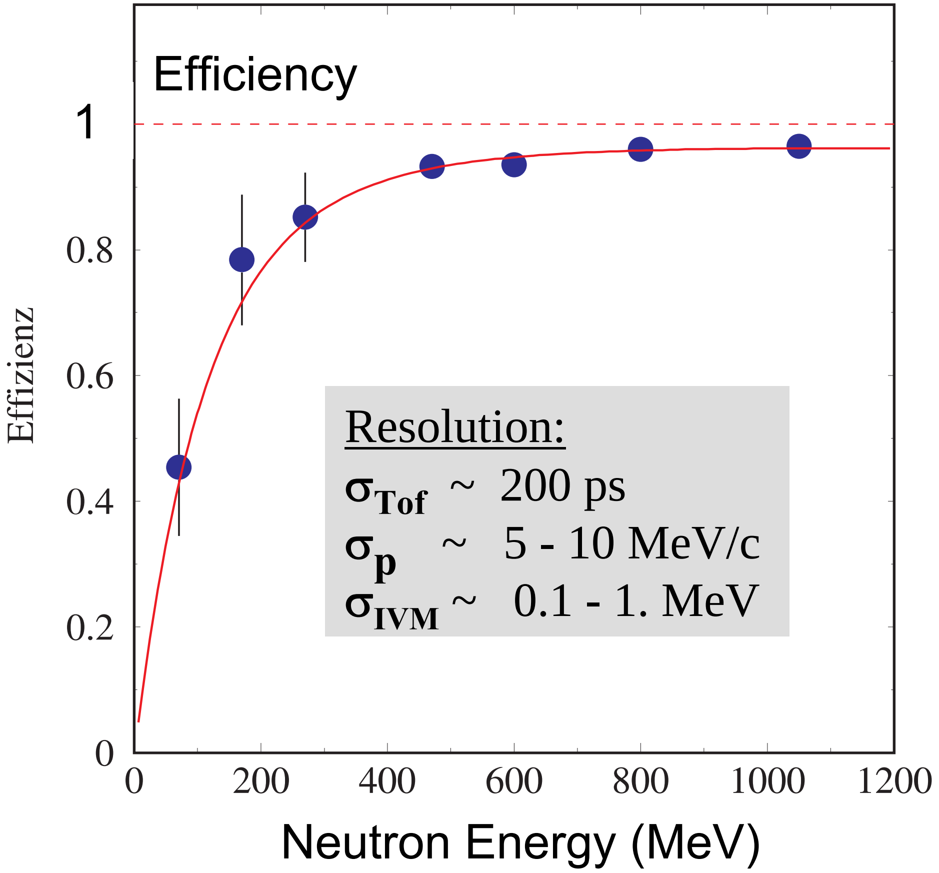
$$E^* = \left(\sqrt{\sum_i m_i^2 + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos\theta_{ij})} - m_{proj}\right) c^2 + E_\gamma$$

The Large Area Neutron Detector LAND



Nucl. Instr. Meth. A314 (1992) 136





Resolution:

σ_{Tof} ~ 200 ps

σ_p ~ 5 - 10 MeV/c

σ_{IVM} ~ 0.1 - 1. MeV

Scattering of Light Neutron-Rich Nuclei Investigated at LAND@GSI

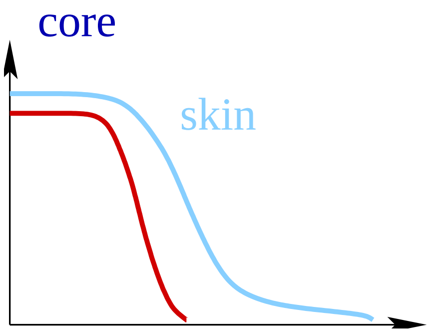
Knockout

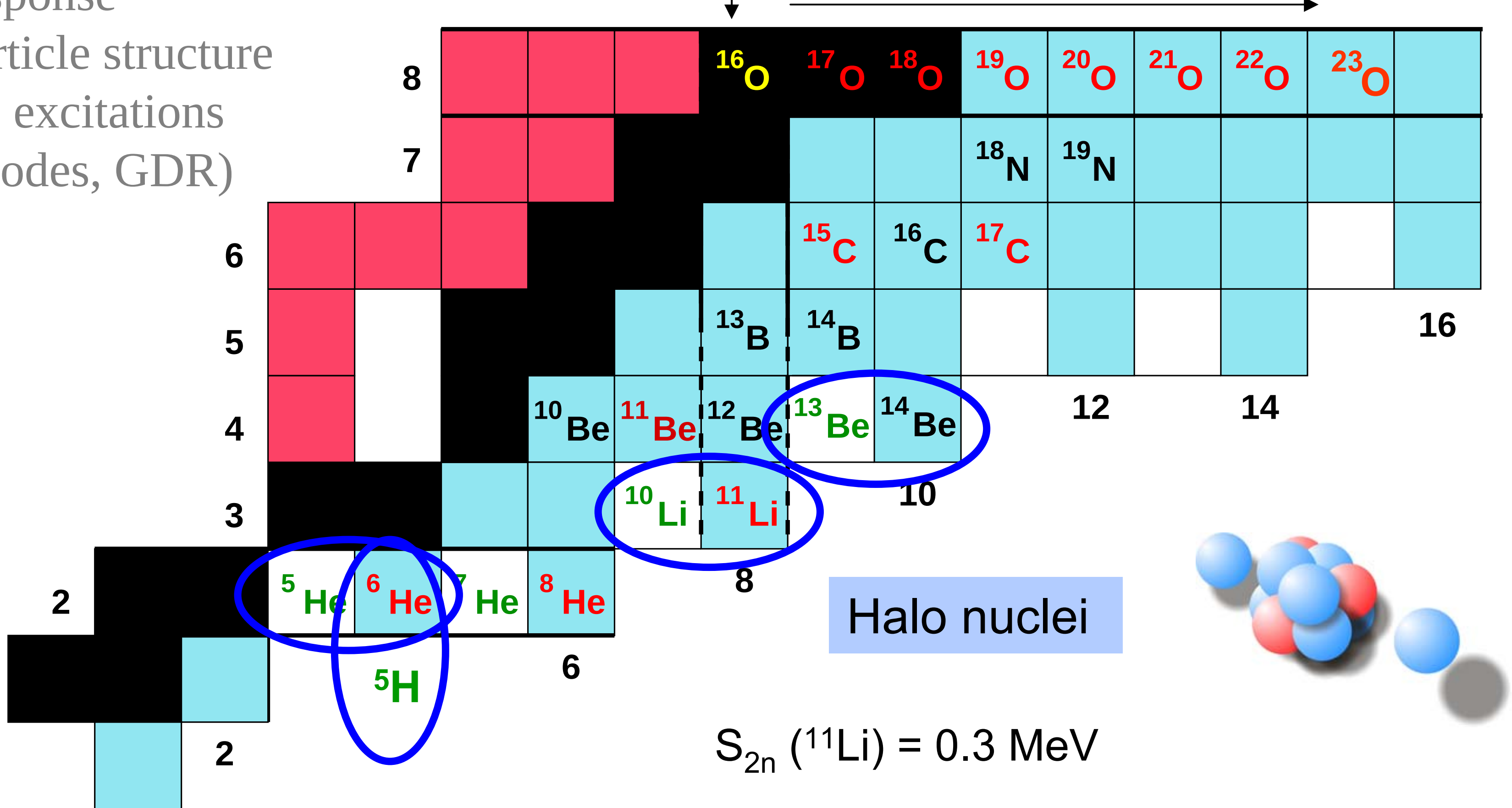
single-particle structure
unbound states

Electromagnetic excitation

dipole response
single-particle structure
collective excitations
(soft modes, GDR)

Neutron skin



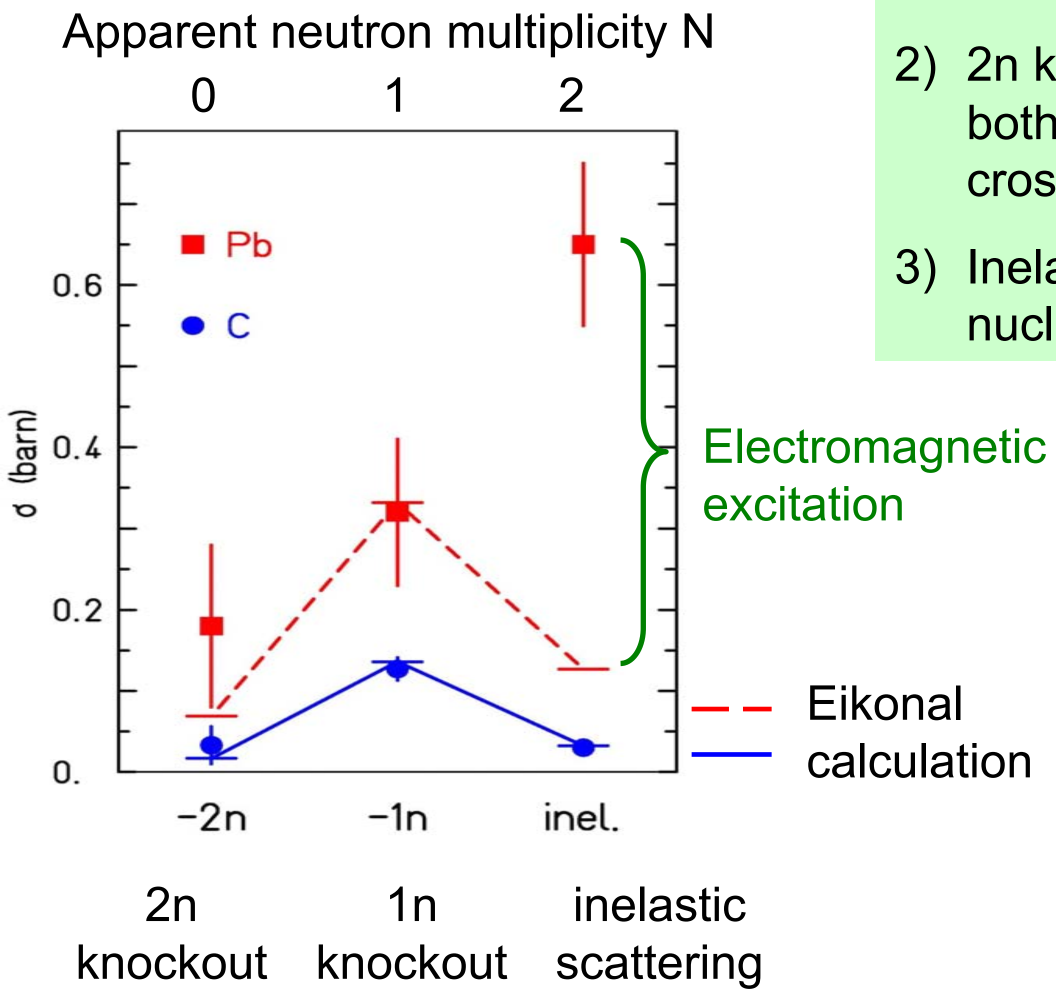


Halo nuclei

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

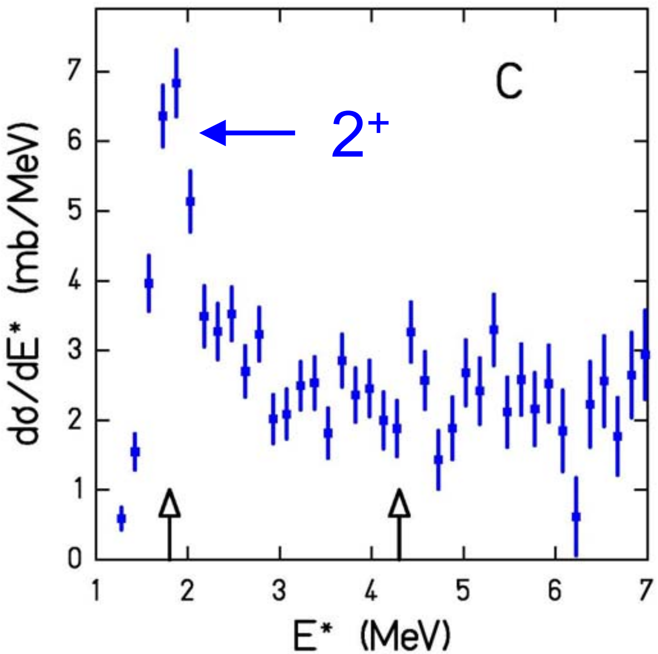
Reaction mechanisms for two-neutron Halo nuclei

^{6}He(@240 MeV/u) + C,Pb $\rightarrow \alpha + xn$



1) 1n knockout:
   one n scattered to large angles (→ N=1)
2) 2n knockout:
   both neutrons react with target (→ N=0)
   cross section sensitive to correlations
3) Inelastic scattering (→ N=2)
   nuclear/electromagnetic excitation

Nuclear excitation of ^{6}He

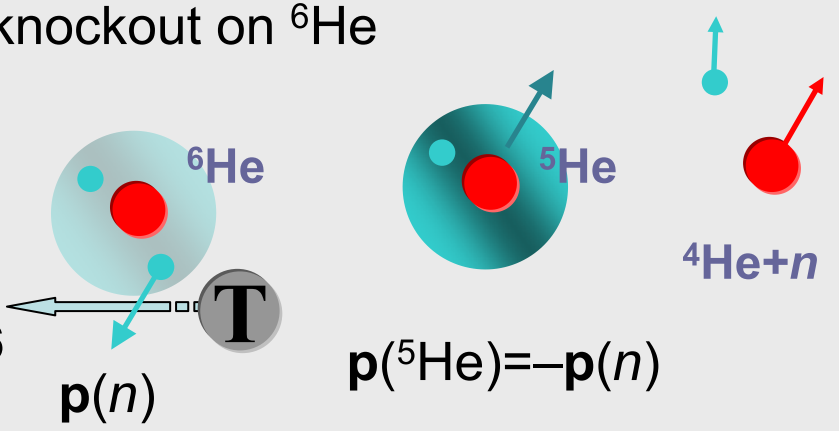


T. Aumann et al., PRC 59 (1999) 1252

Knockout to Continuum States: The ^{6}He test case

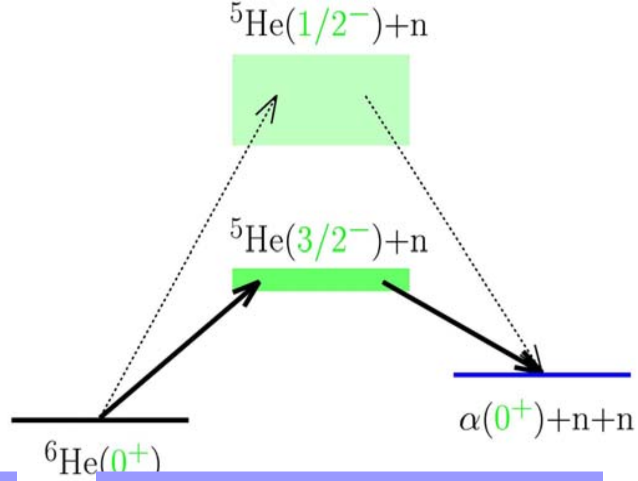
One-neutron knockout on ^{6}He (240 MeV/u):

Two-step process

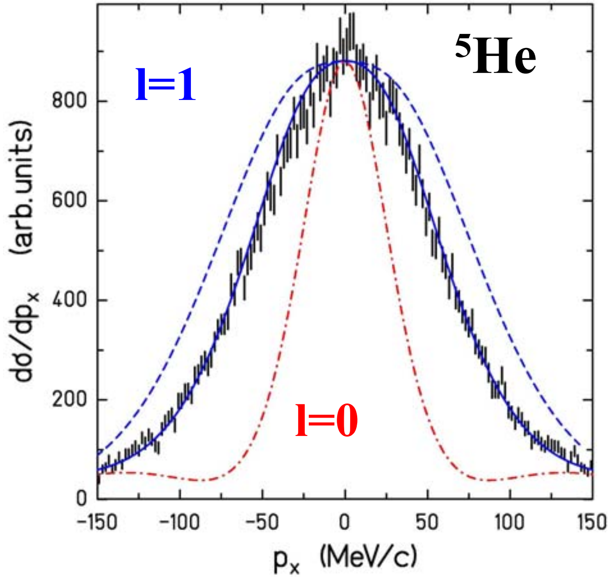


p(*n*)

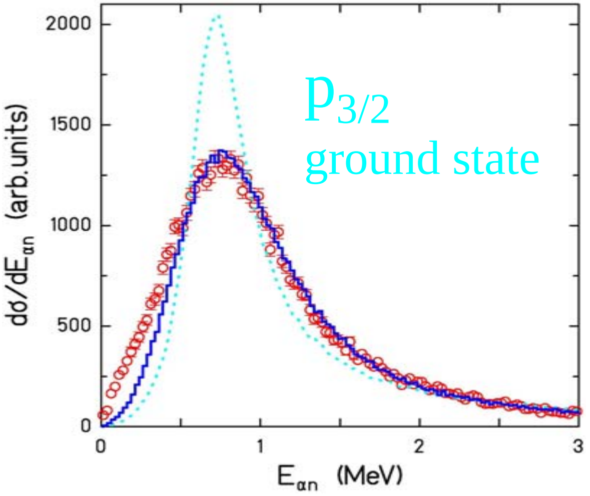
p(^{5}He)=–**p**(*n*)



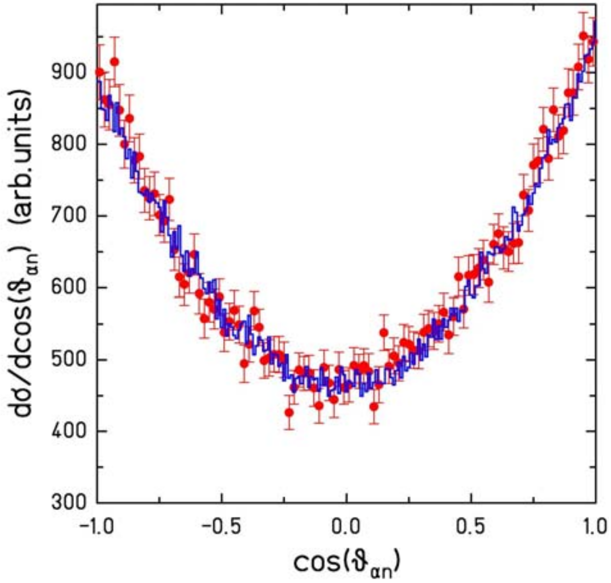
Momentum distribution



Relative energy ^{4}He↔n



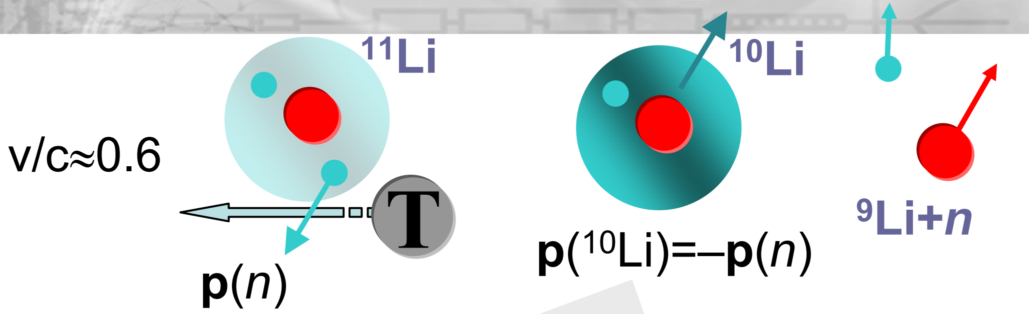
Angular correlation



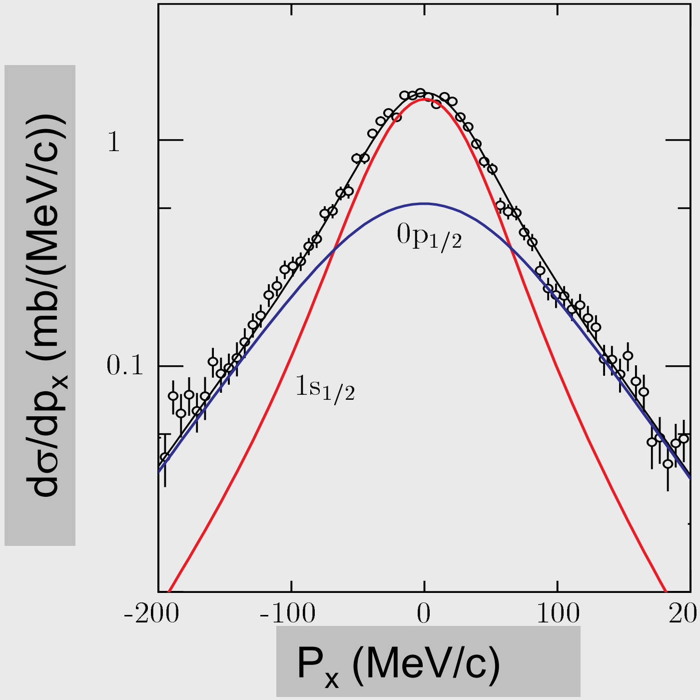
Data: LAND-FRS@GSI, D. Aleksandrov et al., NPA 633 (1998), L. Chulkov et al., PRL 79 (1999) 201

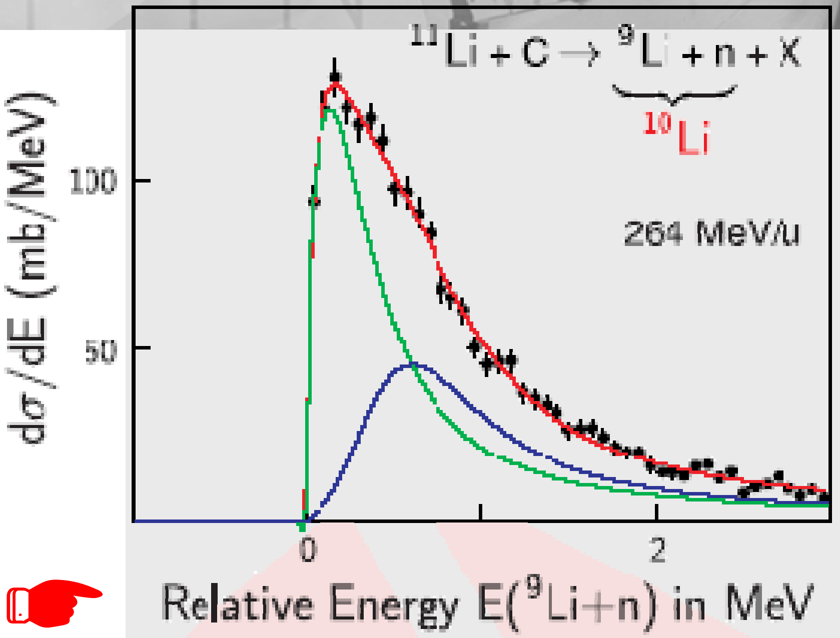
⇒ Structure of 2*n*-halo nuclei, spectroscopy of unbound states

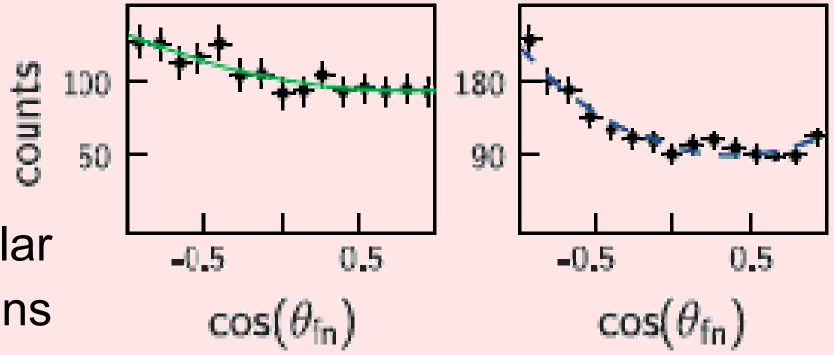
The halo of ^{11}Li: *s* and *p* waves



Momentum distribution ^{10}Li







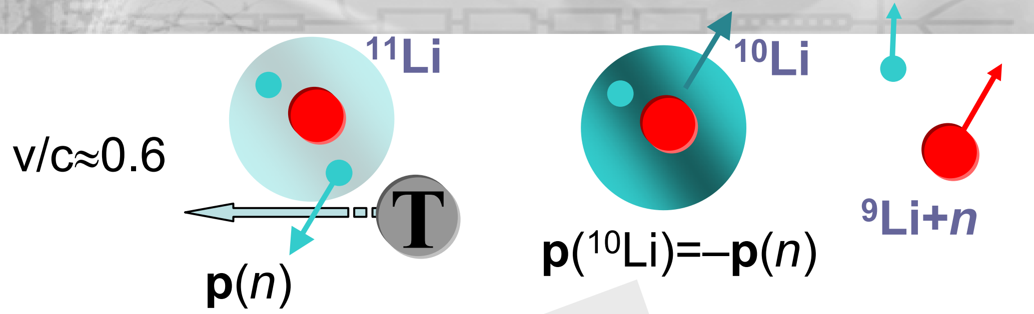
Angular correlations

⇒ **Strong *s*-wave admixture**

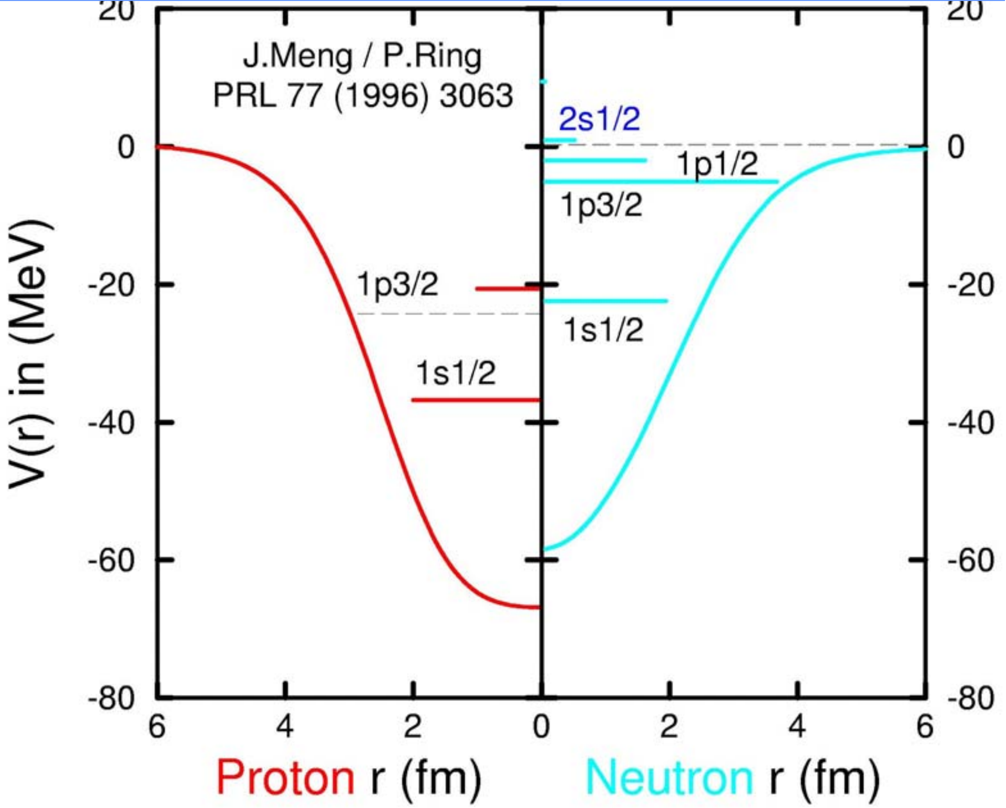
$(s_{1/2})^2$ / $(p_{1/2})^2$ ≈ 1

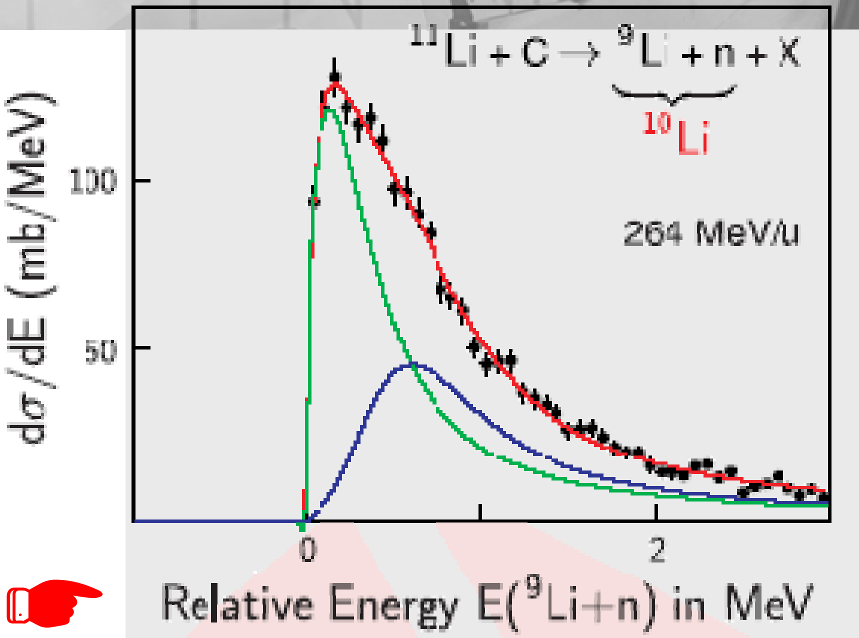
Data: LAND-FRS@GSI, H. Simon et al., Phys. Rev. Lett. 83 (99) 496

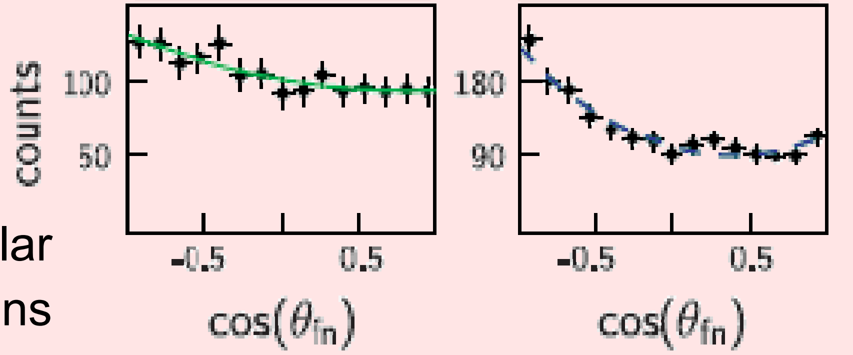
The halo of ^{11}Li: s and p waves



Theory: relativistic mean field





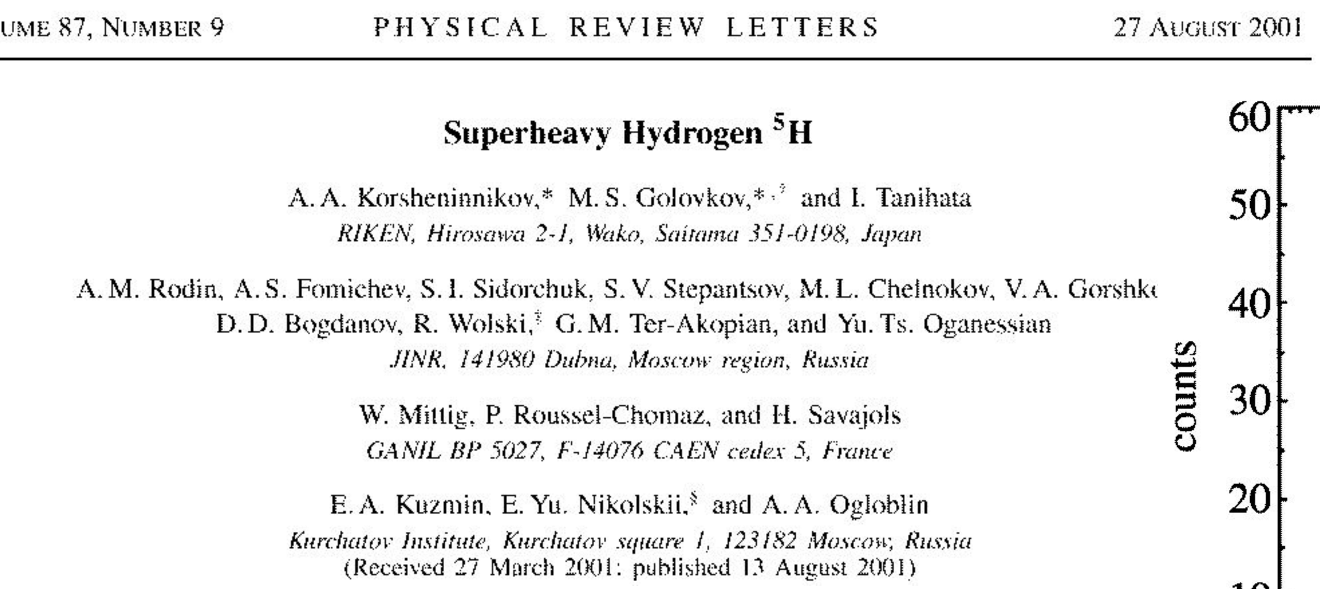


gular

tions

Strong **s-wave** **admixture**

$(s_{1/2})^2$ / $(p_{1/2})^2$ ≈ 1



UME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Superheavy Hydrogen ^{5}H

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A. M. Rodin, A. S. Fomichev, S. I. Sidorchuk, S. V. Stepantsov, M. L. Chelnokov, V. A. Gorshk
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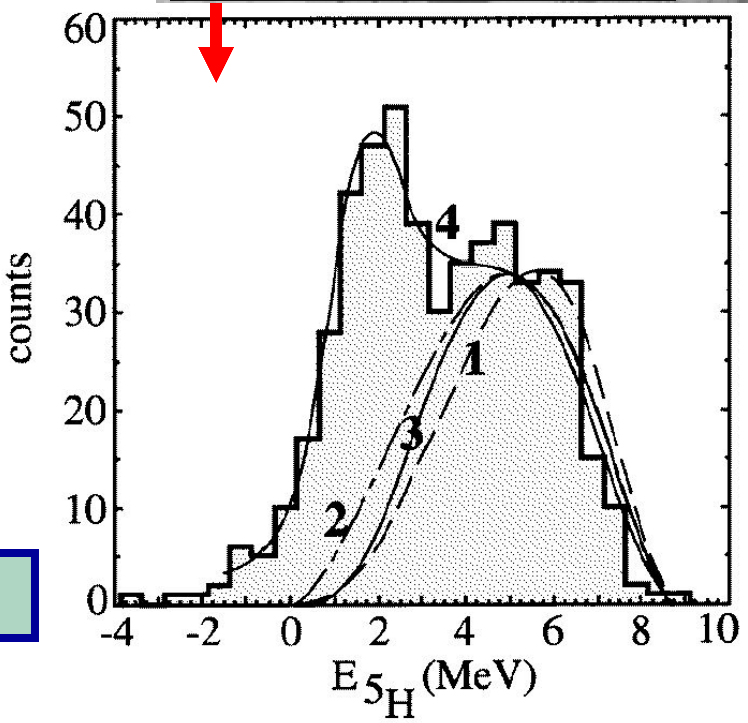
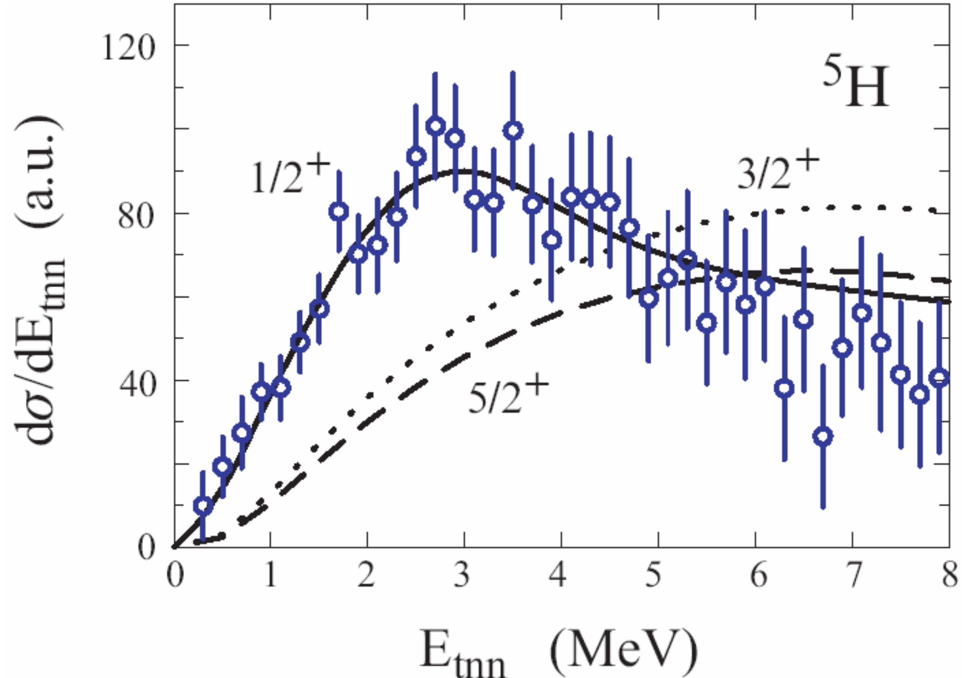
(Received 27 March 2001; published 13 August 2001)

^{6}He (p, ^{2}He) ^{5}H



at GSI : ^{6}He → t + n + n (proton knockout)



notice: different reactions may populate different states !!

Data consistent with 3-body calculation of Shulgina et al (PRC62, 2000, 014312) with

$I^\pi=1/2^+$ ^{5}H ground state

M. Meister et al. , Phys. Rev. Lett. 91 (2003) 162504

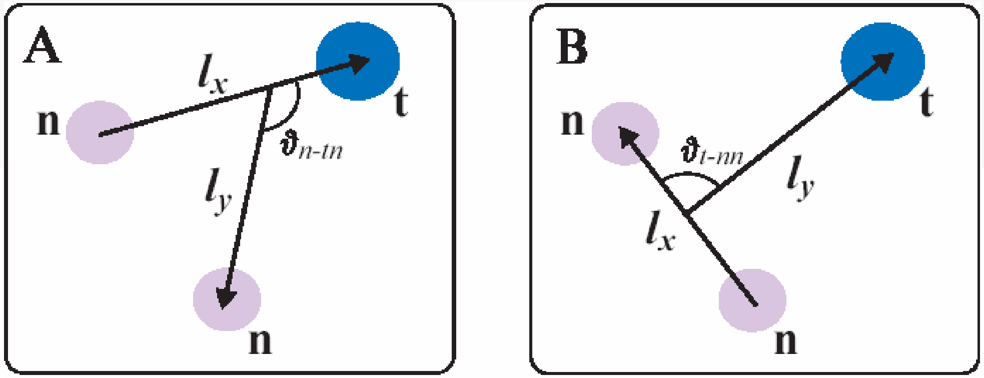
Nucl. Phys. A 723 (2003) 13

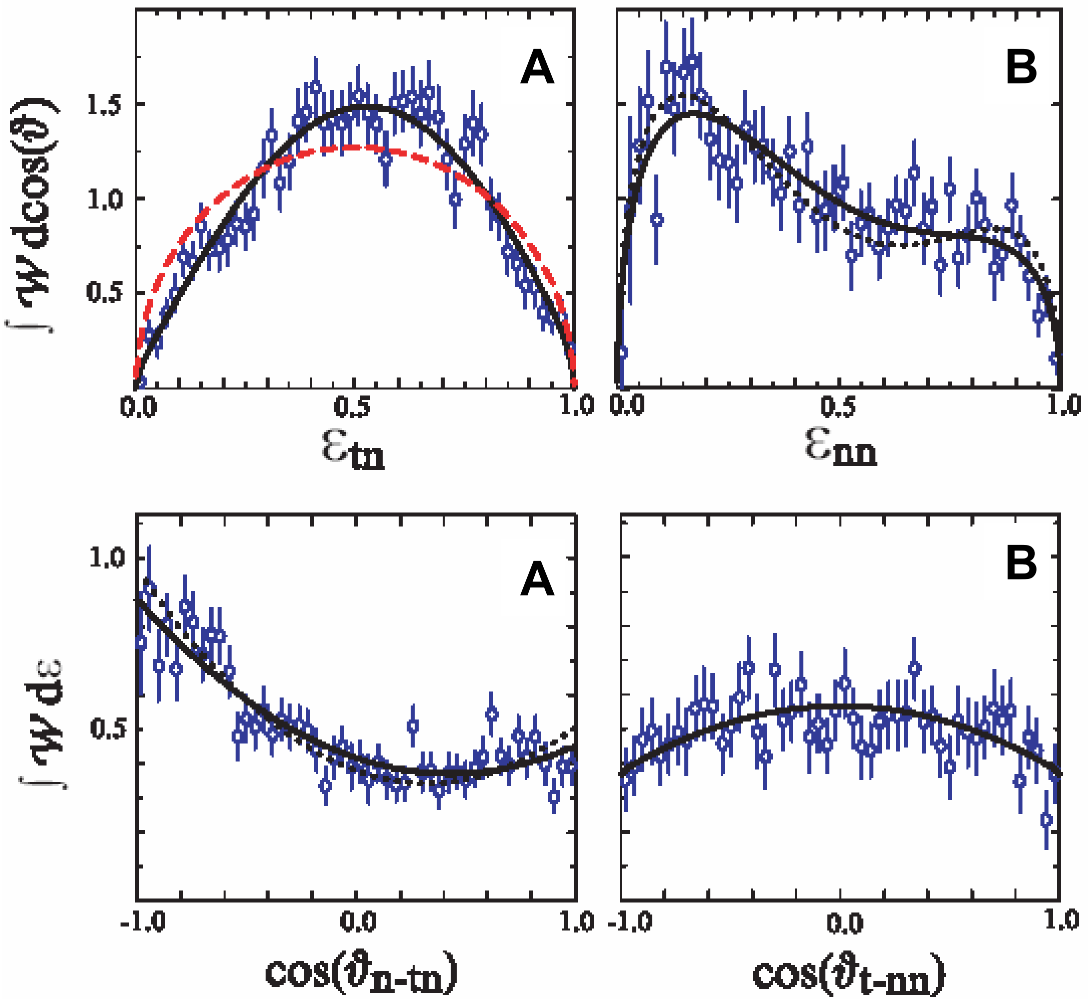
M. Meister et al. ,

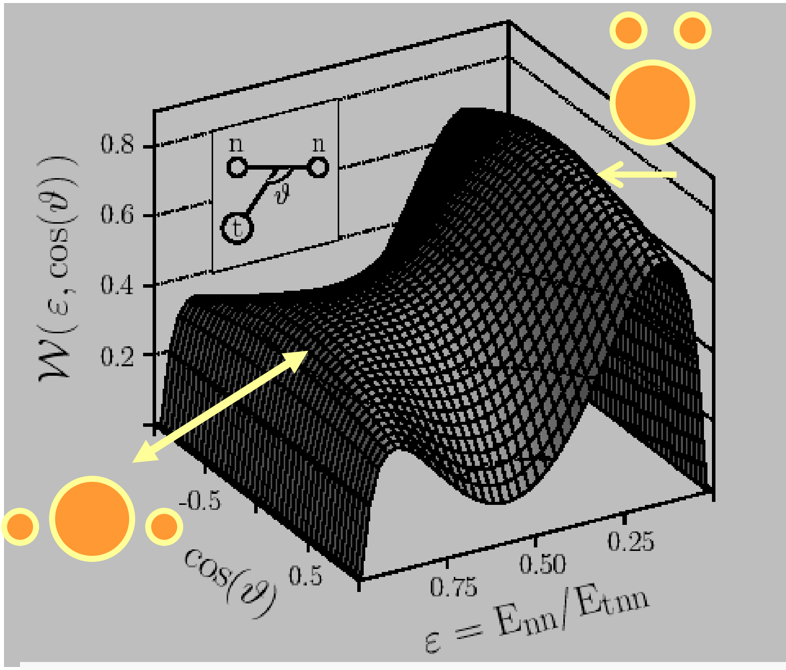
Phys. Rev. Lett. 91 (2003) 162504

3-body coordinate frames

analysis by means of Hyperspherical Harmonics expansion (truncated)







Conclusion Knockout / Halo Nuclei

- Momentum distributions after one-nucleon removal are directly linked to the wave-function of the removed nucleon (at the surface)

- Cross sections are large, in particular for Halo nuclei

- Knockout reaction have been established as a spectroscopic tool
  - coincident γ-ray spectroscopy defines core state
  - or likewise invariant-mass spectroscopy in case of unbound residual states
  - momentum distributions define l-value of knocked-out nucleon
  - cross sections yield spectroscopic factors
  - angular correlations → quantum numbers
    → disentangle overlapping states in the continuum
  - spectroscopy of unbound states (even beyond the drip line)

⇨ Comparison of knockout reactions to Coulomb breakup: next lecture

✔ Introduction: Physics, Experiments, Production

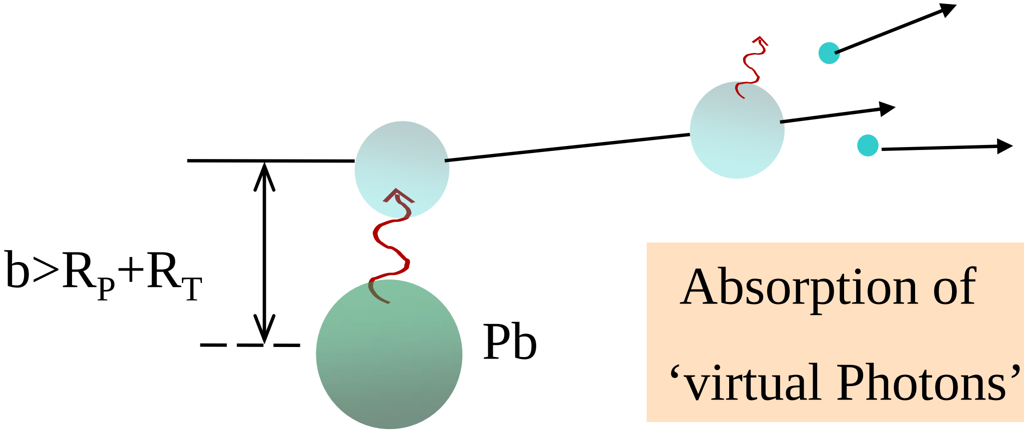
✔ At and beyond the drip line: knockout reactions

☛ **Dipole excitations of neutron-rich nuclei**

  - Coulomb breakup of halo nuclei
  - Giant and Pygmy collective excitations

- Future Developments

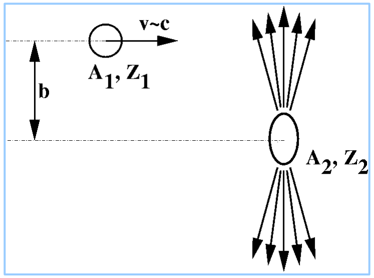
Experimental Approach:
Electromagnetic excitation at high energies



Absorption of

'virtual Photons'

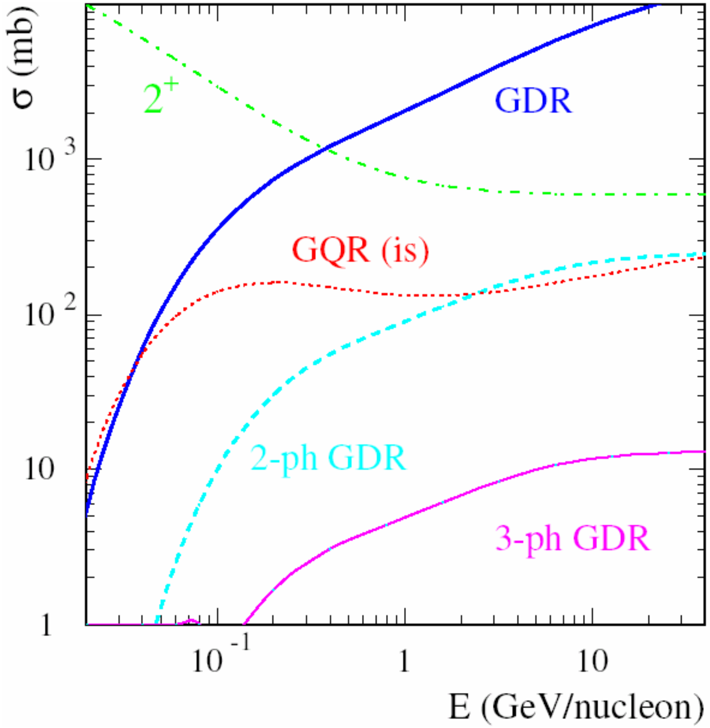
$\sigma_{elm} \sim Z^2$



High velocities v/c≈0.6-0.9
⇒ High-frequency Fourier components
$E_{\gamma,max} \approx 25$ MeV (@ 1 GeV/u)

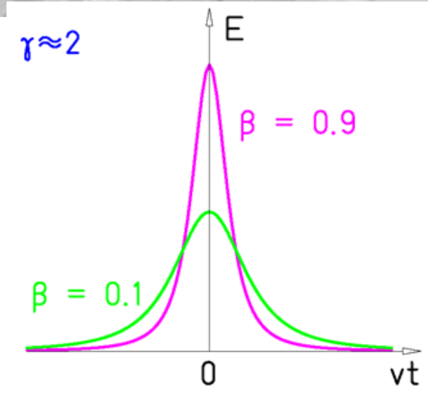
Semi-classical theory:

$$d\sigma_{elm} / dE = N_\gamma(E)\, \sigma_\gamma(E)$$



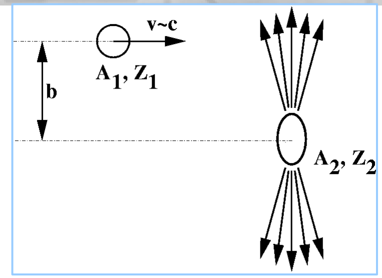
Determination of 'photon energy' (excitation energy) via a kinematically complete measurement of the momenta of all outgoing particles (invariant mass)

Heavy-ion induced electromagnetic excitation at high beam energies



Two effects:

velocity plus Lorentz contraction

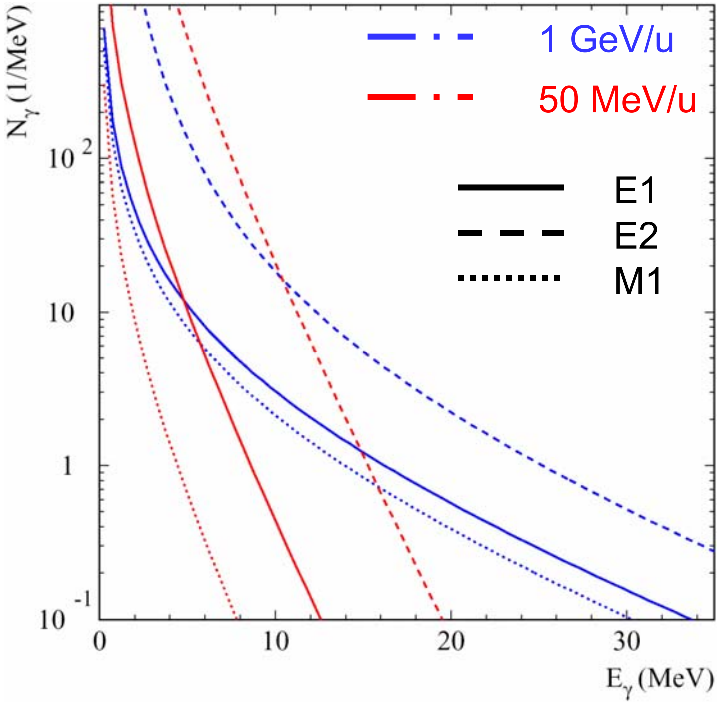


adiabatic cut-off:

$$E_{\max} = \frac{\hbar}{\tau} = \frac{\hbar c \gamma \beta}{b}$$

E_{max}=25MeV
for 1 GeV/u

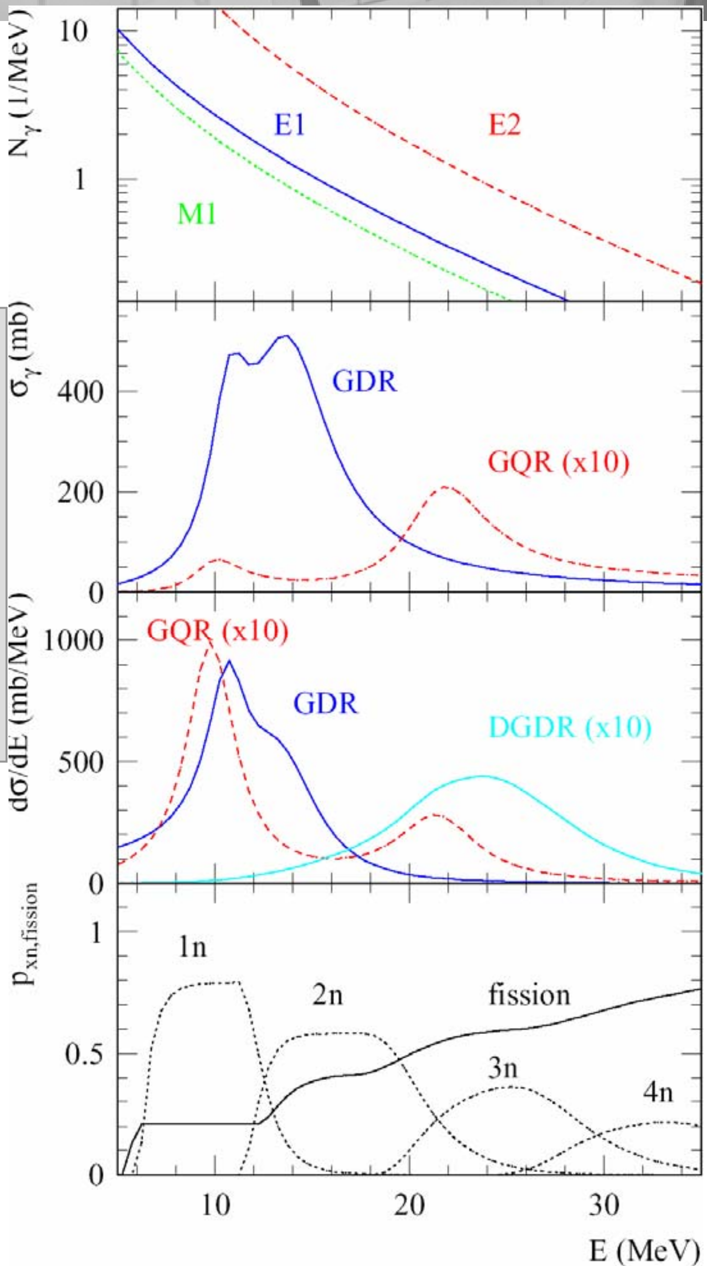
virtual photon spectrum



approaches plane wave

for γ≫1

all $N_{\pi l}$ equal (as for real photon beams)

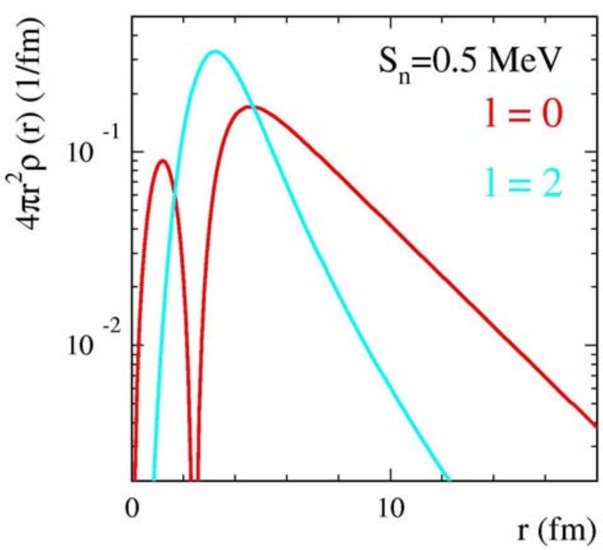


Low-Lying E1 Strength as Spectroscopic Tool

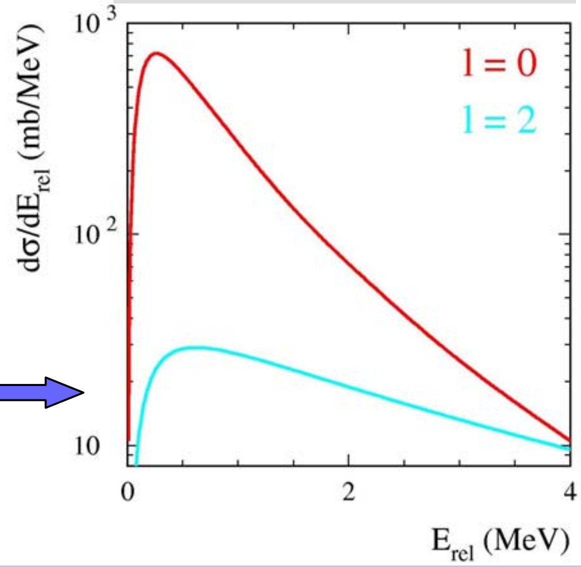
Wave function: e.g. $|^{11}\mathrm{Be}\rangle = \alpha|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle + \beta|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + \ldots$

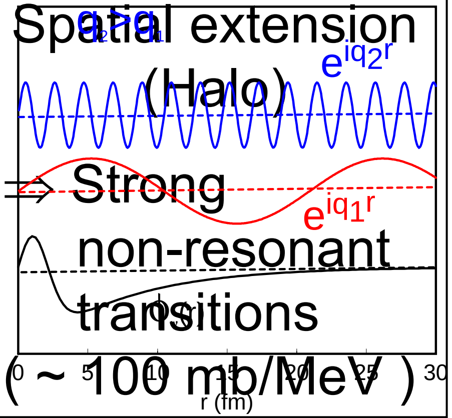
$$\frac{d\sigma(I_c^\pi)}{dE_{rel}} = \frac{16\pi^3}{9\hbar c} N_{E1}(E^*)\, S(I_c^\pi, nlj) \sum_m \left|\left\langle q \left| \frac{Ze}{A} r Y_m^l \right| \Phi_{nlj} \right\rangle\right|^2$$

Density distribution



Differential cross section





Spatial extension (Halo)

⇒ Strong non-resonant transitions

(~ 100 mb/MeV)

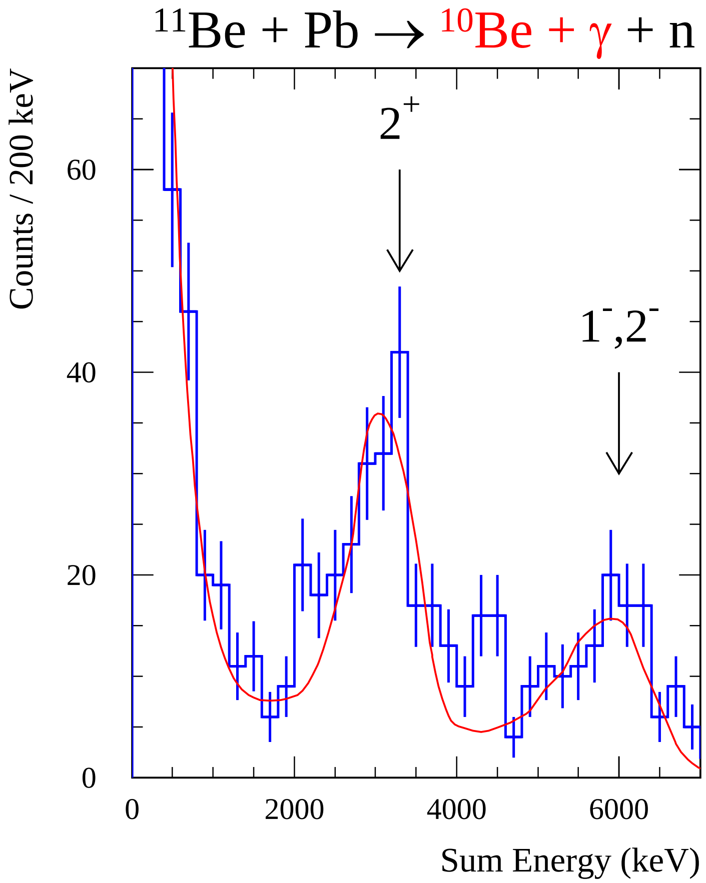
Shape of differential cross section ⇒ angular momentum *l*

γ-ray coincidence ⇒ identification of core state

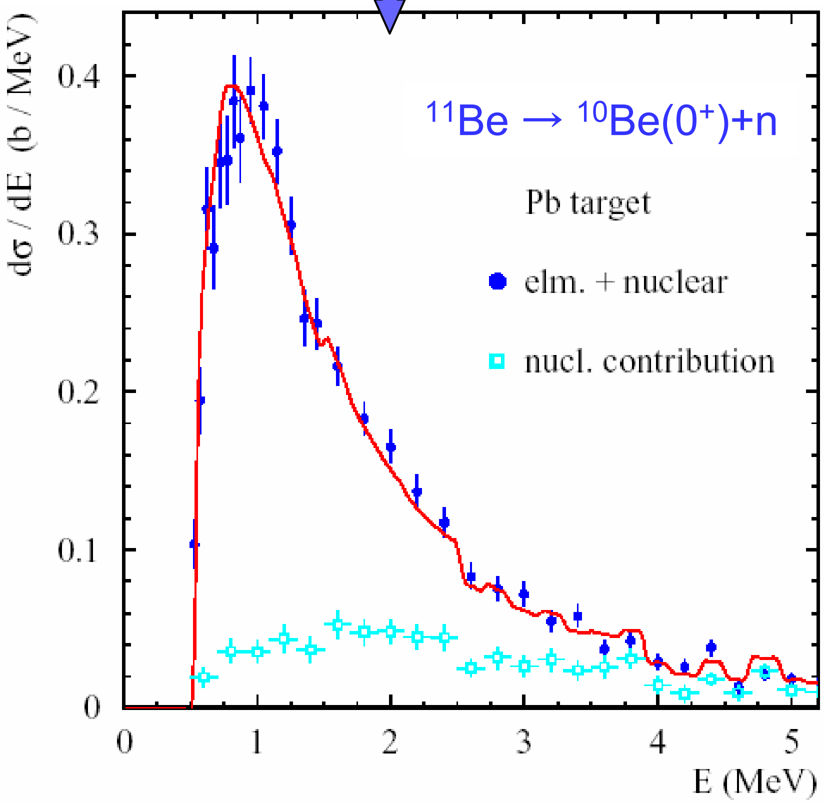
Cross section ⇒ spectroscopic factor

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

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



ph states at 6 MeV (inner shell p neutrons lifted into continuum)



R. Palit et al., PRC 68 (2003) 034218

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

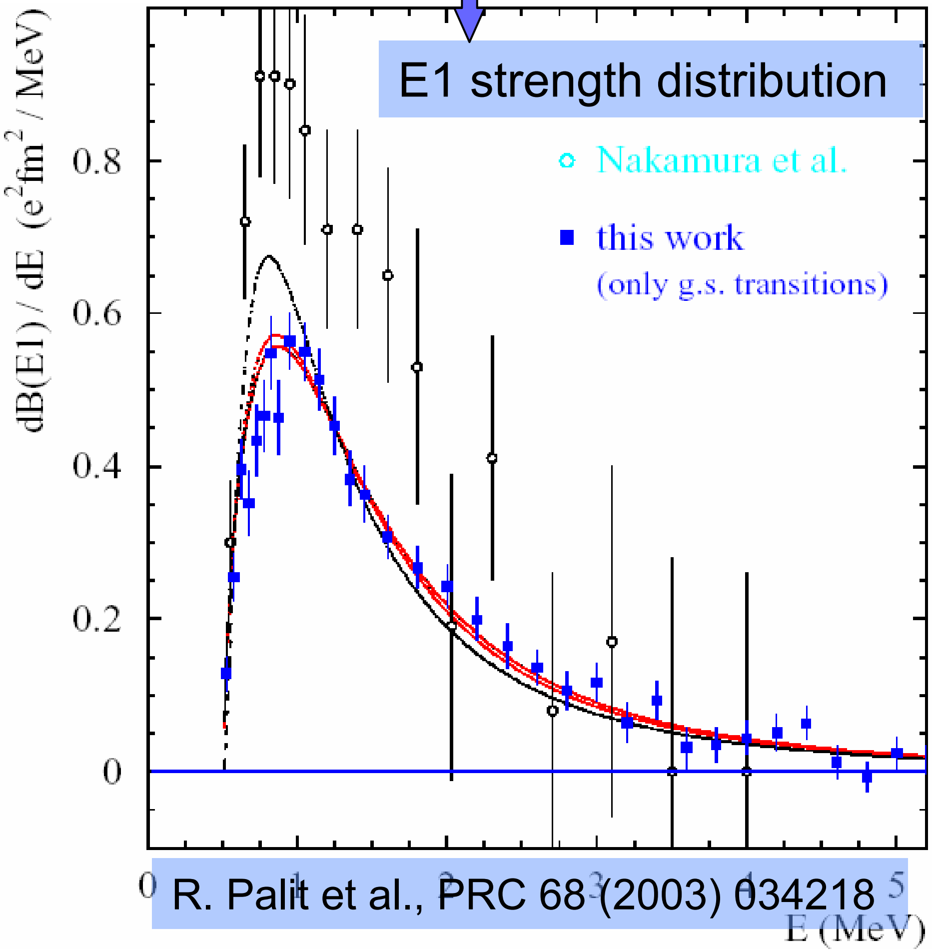
$$|^{11}\mathrm{Be}> \;=\; \sqrt{S(2^+)}\;|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}> \;+\; \underbrace{\sqrt{S(0^+)}\;|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}>}\; + \ldots$$

Spectroscopic factor

Analysis in the effective range approach:

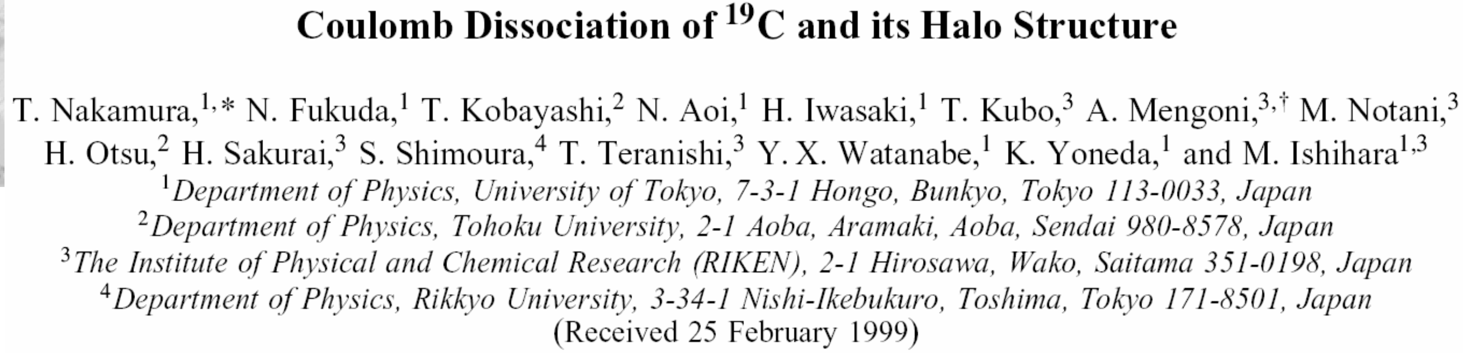
$S(0^+)=0.70(5)$

S. Typel, G. Baur, PRL **93** (2004) 142502



E1 strength distribution

R. Palit et al., PRC 68 (2003) 034218



Coulomb Dissociation of ^{19}C and its Halo Structure

T. Nakamura,[1,*] N. Fukuda,[1] T. Kobayashi,[2] N. Aoi,[1] H. Iwasaki,[1] T. Kubo,[3] A. Mengoni,[3,†] M. Notani,[3]
H. Otsu,[2] H. Sakurai,[3] S. Shimoura,[4] T. Teranishi,[3] Y. X. Watanabe,[1] K. Yoneda,[1] and M. Ishihara[1,3]
[1]*Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
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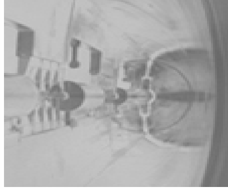
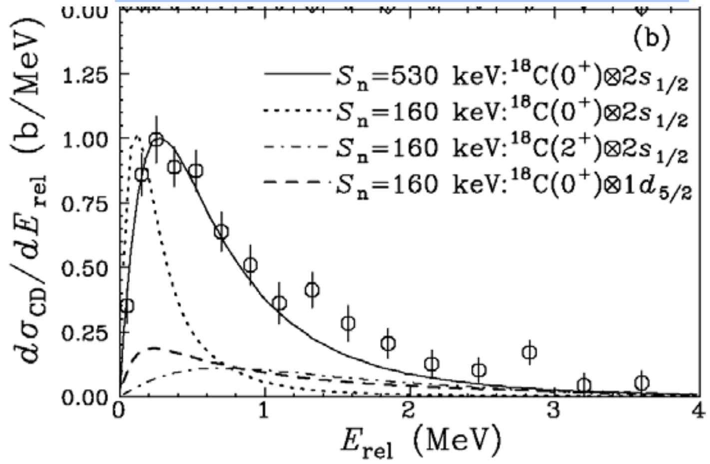
[3]*The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[4]*Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan*
(Received 25 February 1999)

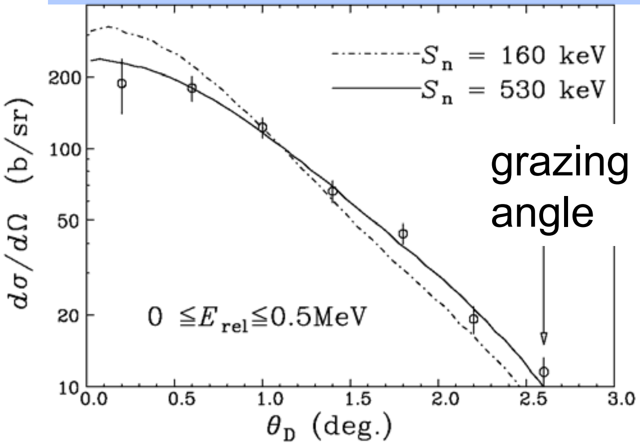


PRL 83
(1999)
1112

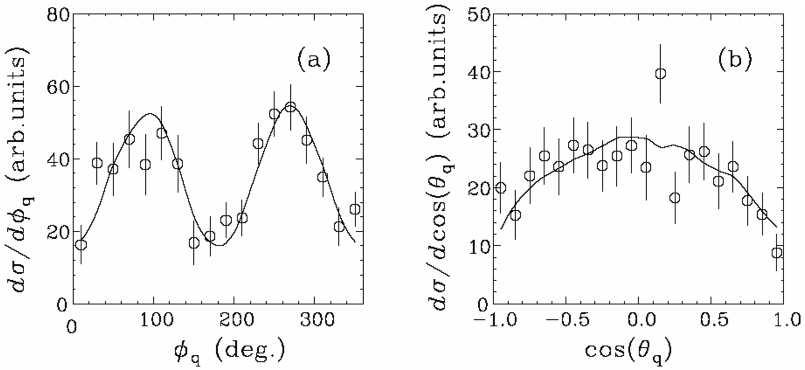
Relative-energy distribution



Differential cross section as a function of the scattering angle



Angular distributions



Results from the measurement with an intensity of 300 ions/sec only:

→ dominantly dipole excitations

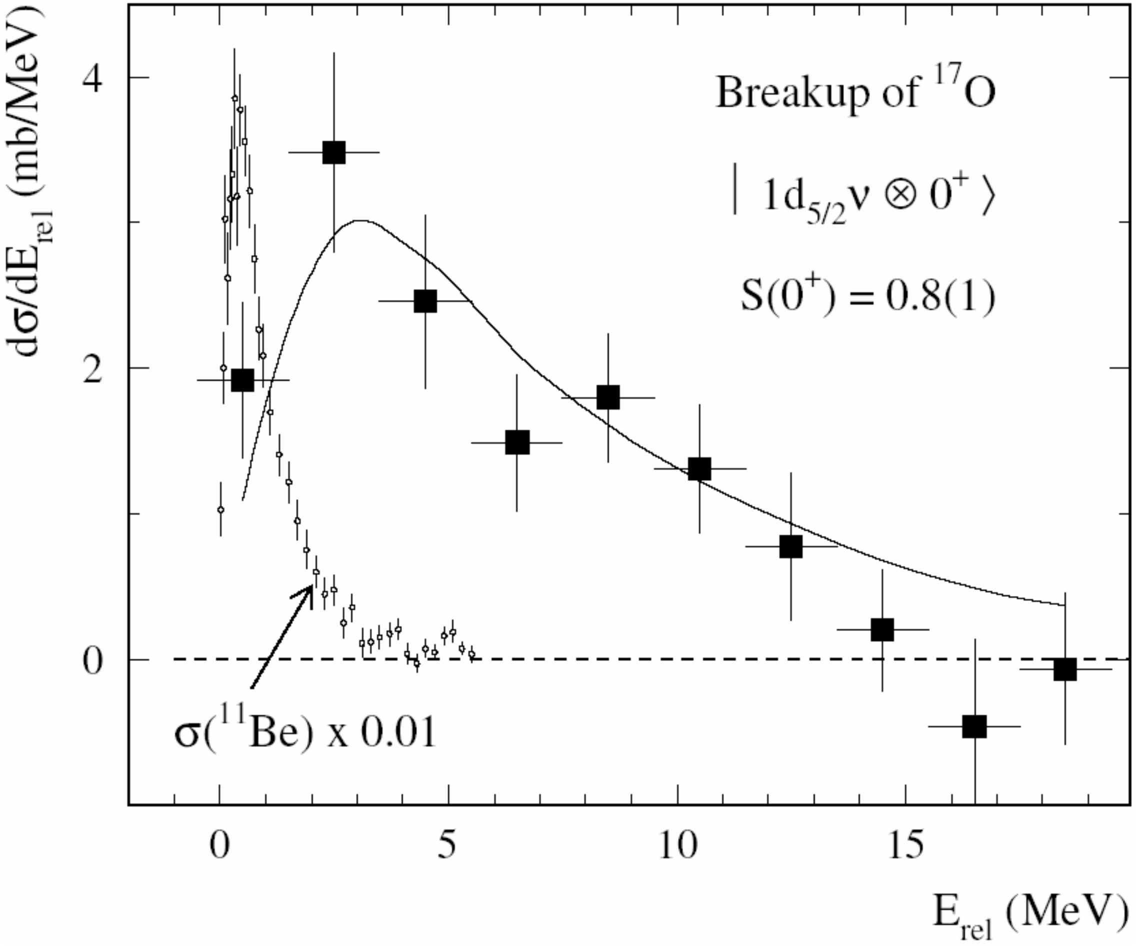
→ ground state spin $I^\pi=1/2^+$

→ ^{18}C(0$^+$)⊗1$s_{1/2}$: S = 0.67

→ separation energy S_n=530(130) keV

Sensitivity of Coulomb breakup

Comparison of the one-neutron halo ^{11}Be with the well bound ^{17}O d neutron



Coulomb breakup is very sensitive to extended neutron-density distributions (halo)

→ applicability as a spectroscopic tool mainly for weakly bound nuclei (large cross sections)

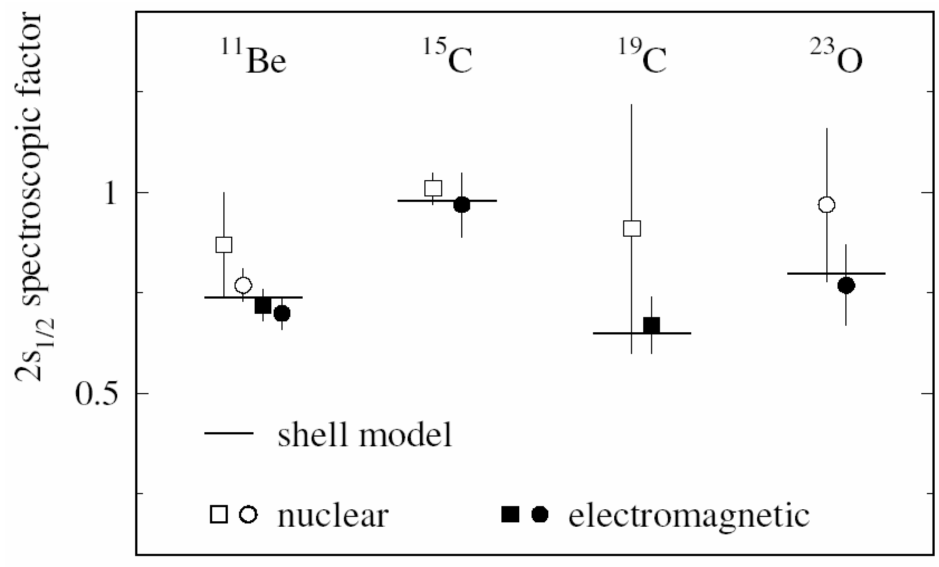
R. Palit et al.,

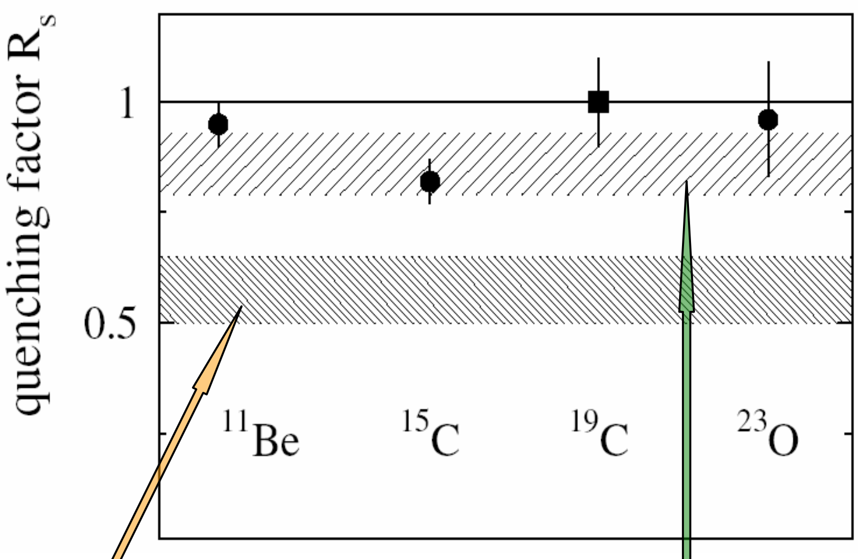
NPA 731 (2004) 235

Absolute single-particle occupancies

Spectroscopic factors for $2s_{1/2}$ halo states derived from nuclear and Coulomb breakup in comparison to the shell model

Ratio of experimental occupancies to shell-model values





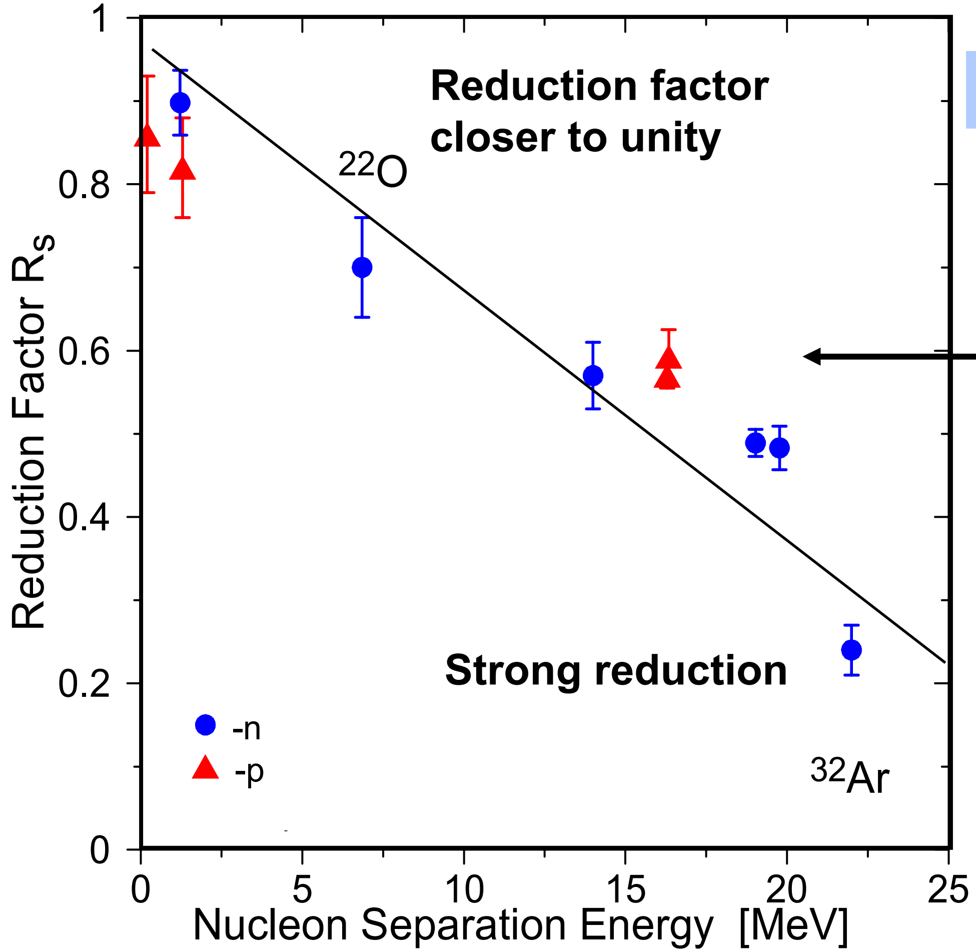
Typical reduction observed for stable nuclei (deduced from electron-induced knockout reactions)

effect of short-range correlations

Halo states

(almost free nucleons)

Isospin dependence of nucleon-nucleon correlations



Reduction factor closer to unity

Strong reduction

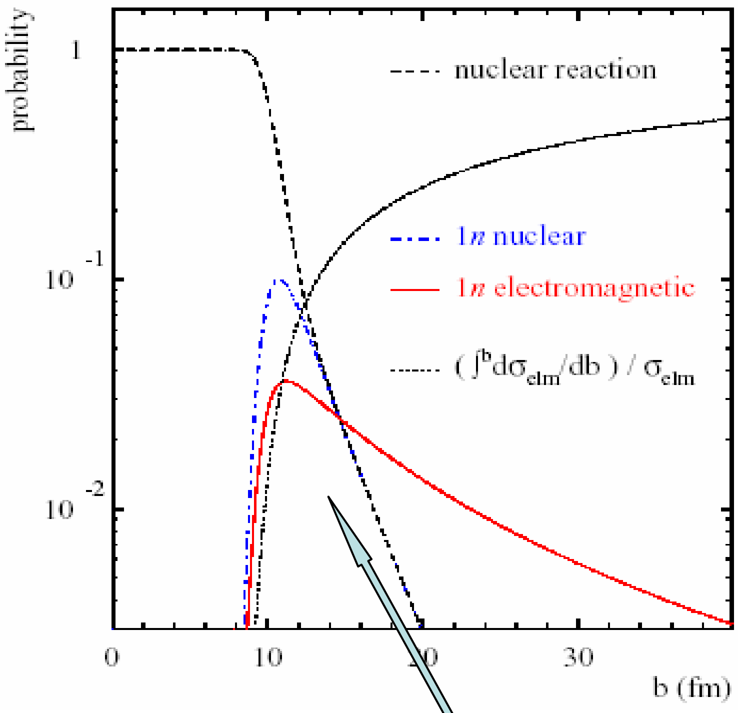
One-nucleon removal reactions

Known reduction in agreement with (e,e'p)

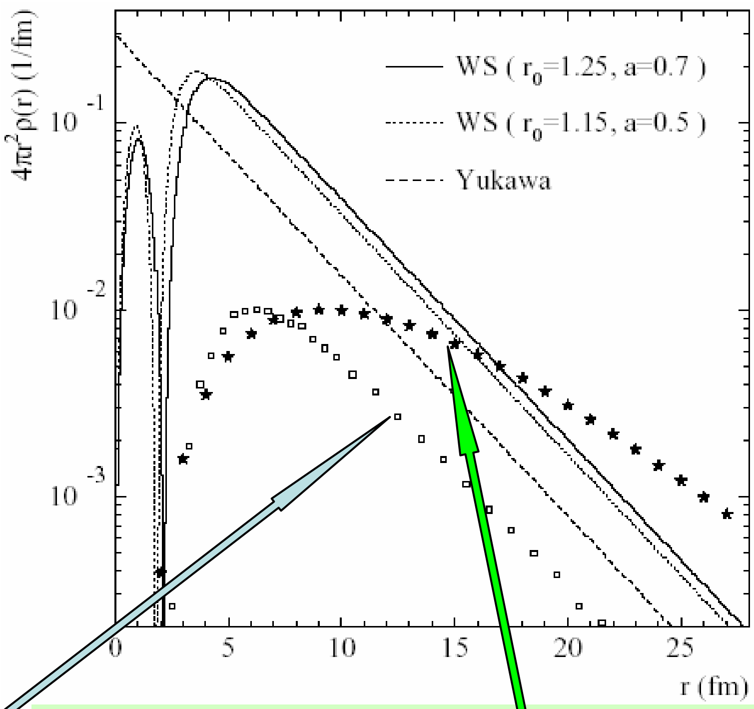
A. Gade et al.,
PRL 93 (2004) 042501

Sensitivity of Coulomb and nuclear breakup

Reaction probabilities



Halo-Neutron Densities



Nuclear breakup

Coulomb breakup

Overlap with continuum wave function

Sensitivity to the tail of the wave function only

Alternative approach: quasi-free scattering: (p,2p), (p,pn) etc. at LAND and R3B

or (e,e'p) at the e-A collider at FAIR

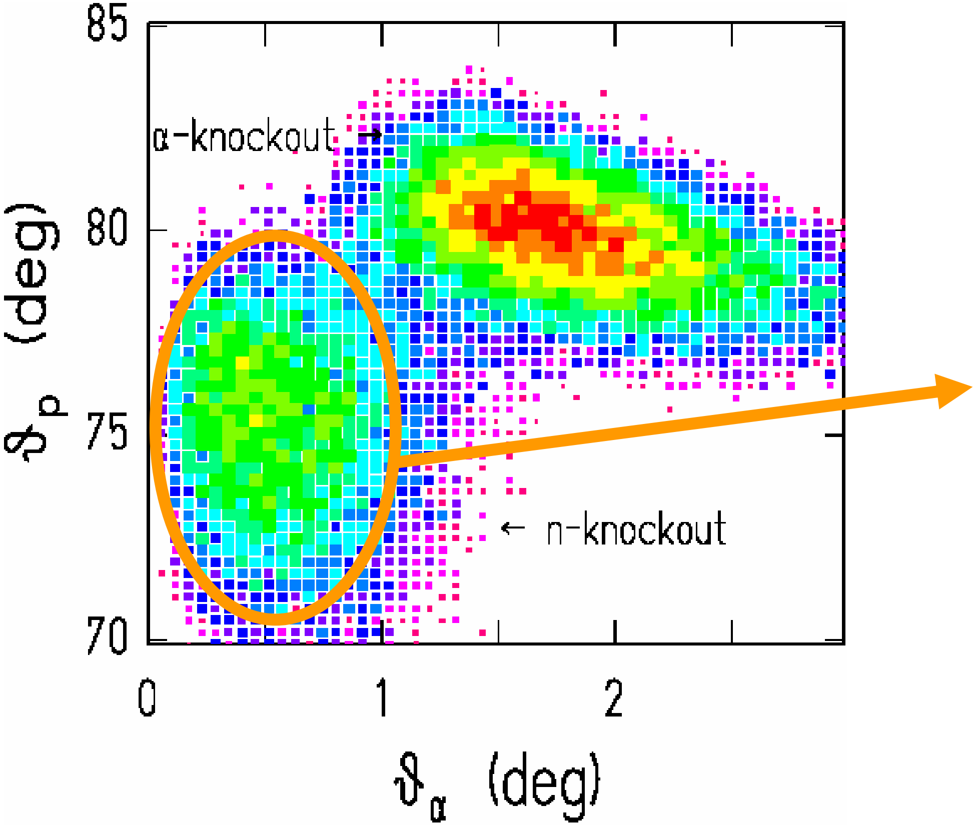
Future: Quasi-free scattering in inverse kinematics

- kinematical complete measurement of
  (p,pn), (p,2p), (p,pd), (p,α), ... reactions
- redundant experimental information:
  kinematical reconstruction from proton momenta
  plus gamma rays, recoil momentum, invariant mass
- sensitivity not limited to surface
  → spectral functions
  → knockout from deeply bound states
- cluster knockout reactions

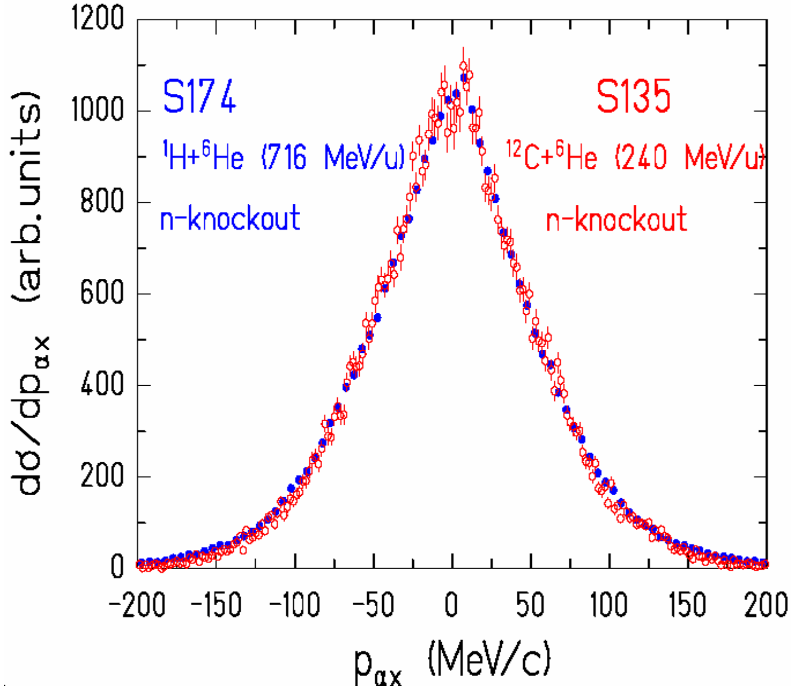
Quasi-free cluster knockout

Experiment S174: Proton elastic scattering (P. Egelhof et al.)

$^{6}He + p \rightarrow \alpha + p' + X$



Momentum distribution



Spectroscopic factors:

neutron: 1.7(2)

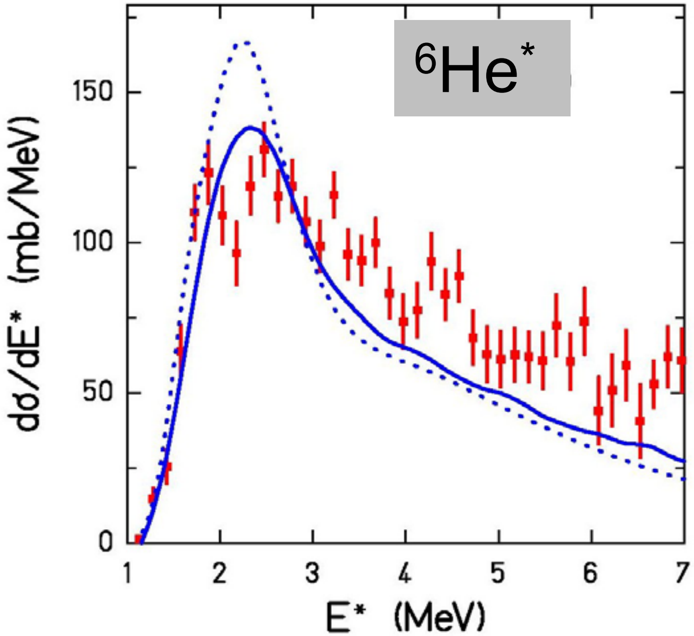
alpha: 0.8(1)

L. Chulkov et al., NPA 759(2005) 43

Electromagnetic excitation of ^{6}He

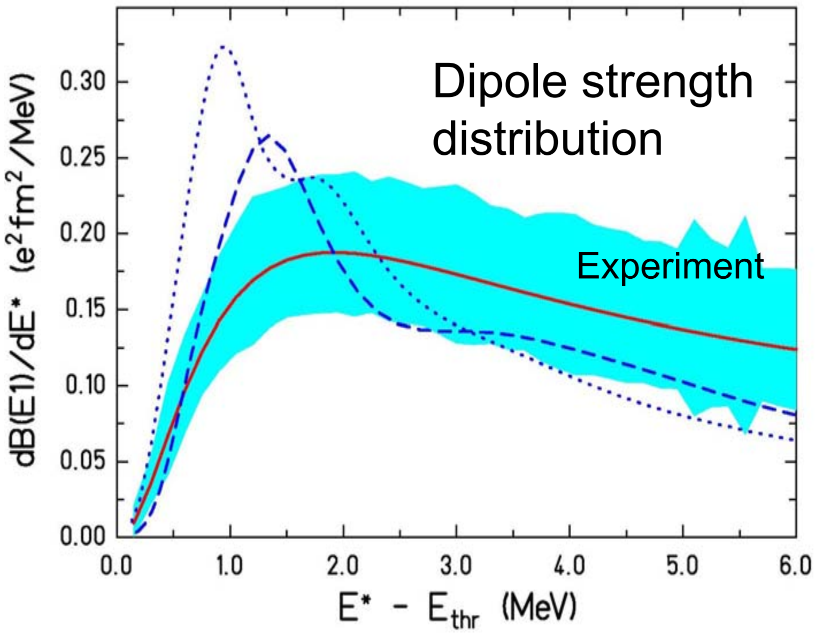
$$^{6}\mathrm{He} + \mathrm{Pb} \rightarrow \underbrace{^{4}\mathrm{He} + 2\mathrm{n}}_{\downarrow}$$

Invariant Mass



Semiclassical calculation

$d\sigma/dE^{*} \sim N_{\gamma}(E^{*})\, dB(E1)/dE^{*}$



Non-energy-weighted dipole sum rule:

$$S_{NEW} = 3/4\ \pi\ Z^{2}e^{2}\ (N_{h}/A_{c})^{2}\ \langle R_{cm\text{-}h}{}^{2}\rangle$$

Spatial correlation from dipole strength:

$$\langle R_{\alpha\text{-}2n}{}^{2}\rangle^{1/2} = 3.36 \pm 0.39 \text{ fm}$$

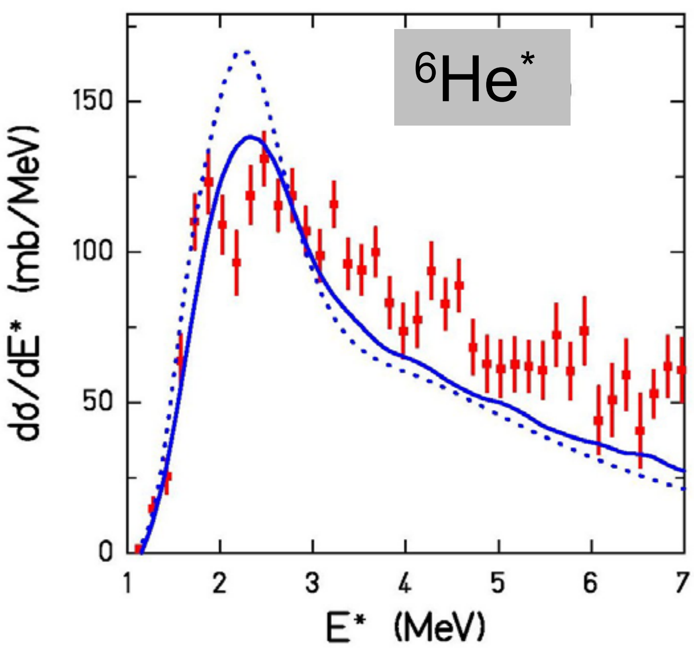
$$\langle R_{cm\text{-}2n}{}^{2}\rangle^{1/2} = 2.24 \pm 0.26 \text{ fm}$$

T. Aumann et al.,
PRC 59 (1999) 1252

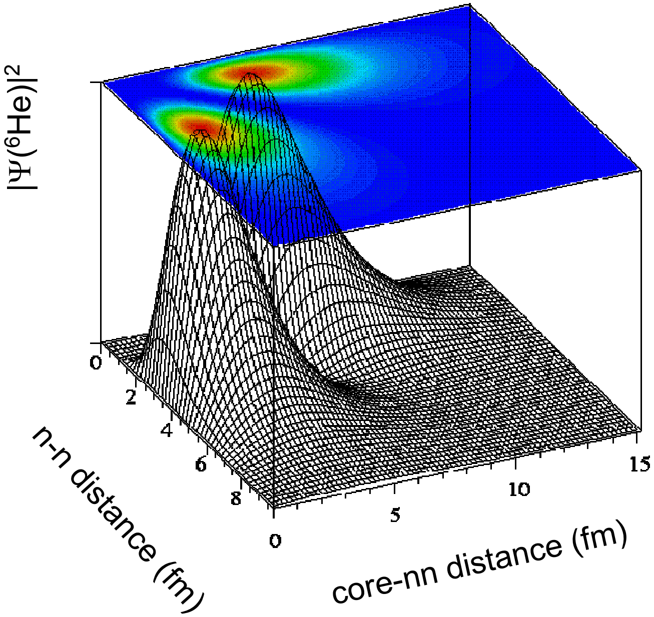
Sagawa 3b-model: $\langle R_{\alpha\text{-}2n}{}^{2}\rangle^{1/2} = 3.63$ fm

Electromagnetic excitation of ^{6}He

$$^6\mathrm{He} + \mathrm{Pb} \rightarrow \underbrace{^4\mathrm{He} + 2n}_{\text{Invariant Mass}}$$



3-body calculation (Danilin et al)



Non-energy-weighted dipole sum rule:

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Spatial correlation from dipole strength:

$$<R_{\alpha\text{-}2n}{}^2>^{1/2} = 3.36 \pm 0.39 \text{ fm}$$

$$<R_{cm\text{-}2n}{}^2>^{1/2} = 2.24 \pm 0.26 \text{ fm}$$

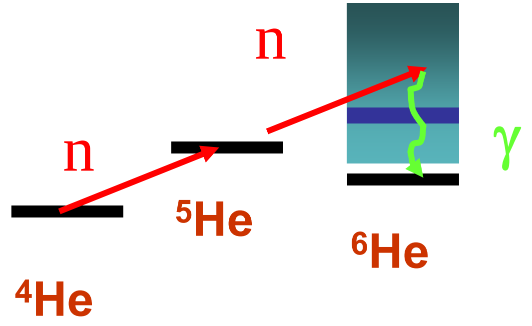
T. Aumann et al.,
PRC 59 (1999) 1252

Sagawa 3b-model: $<R_{\alpha\text{-}2n}{}^2>^{1/2} = 3.63$ fm

Astrophysics: Bridging the mass A=5 and A=8 gaps

R-process nucleosynthesis (type-II supernova ; neutron-star merging): **^{4}He(2n,γ) ^{6}He** **and** **^{6}He(2n,γ) ^{8}He** in the preceding α process may be relevant in bridging the A = 5 and A = 8 mass instability gaps

Dominant:
non-resonant radiative capture

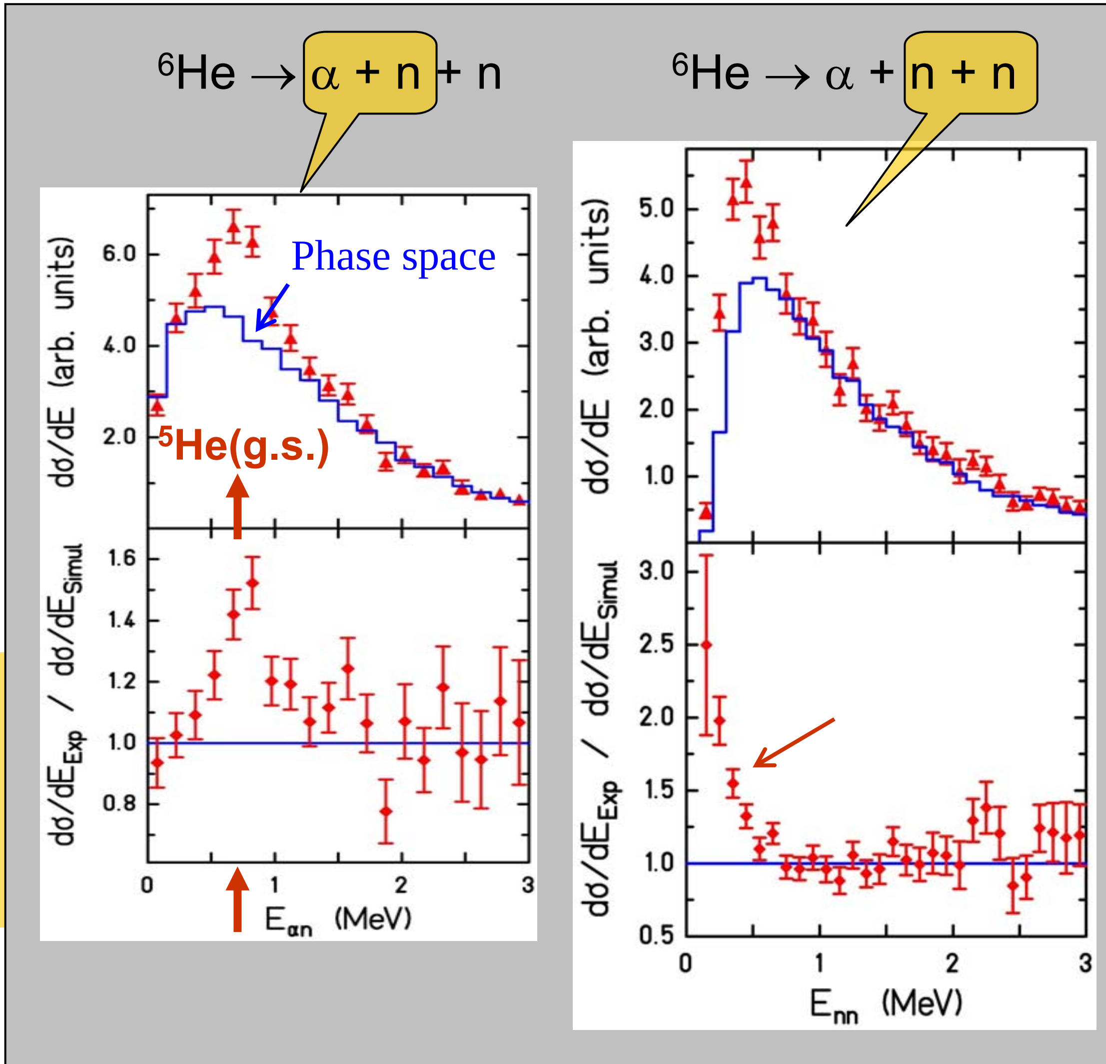


Here:

^{6}He (γ_{virt},n) → ^{5}He(g.s.) → ^{4}He+n

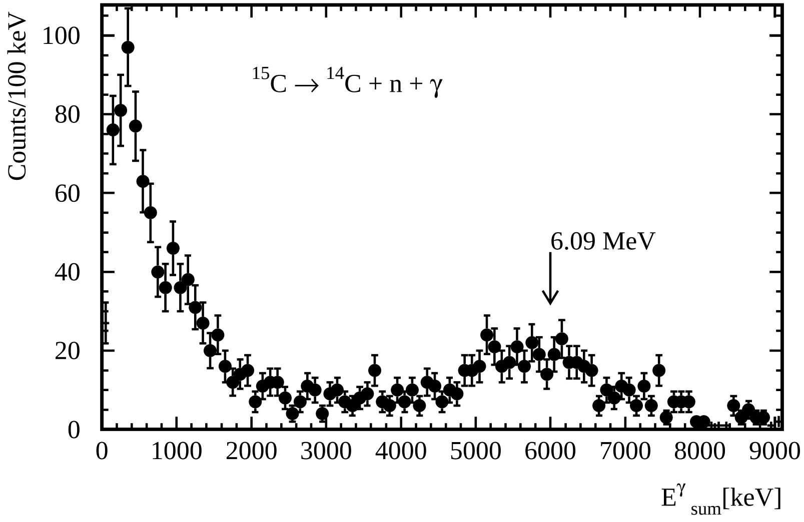
Result: σ_{γ} ~ 1.6 mb MeV

T. Aumann et al., PRC 59 (1999) 1252

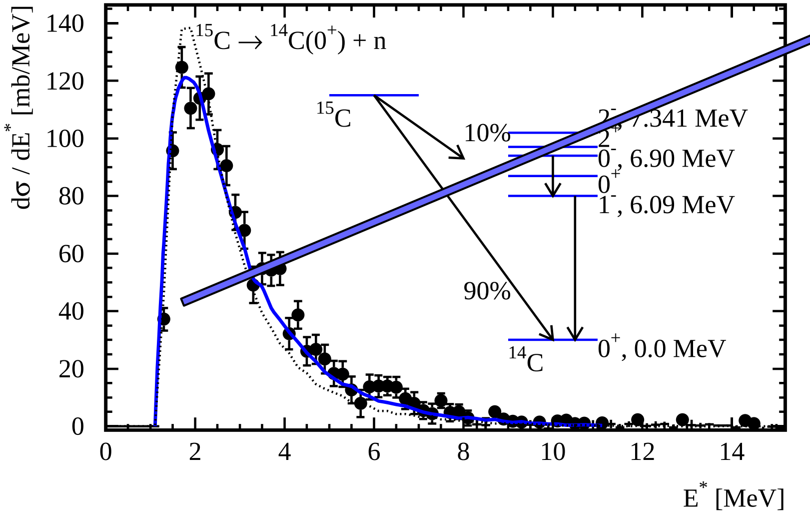


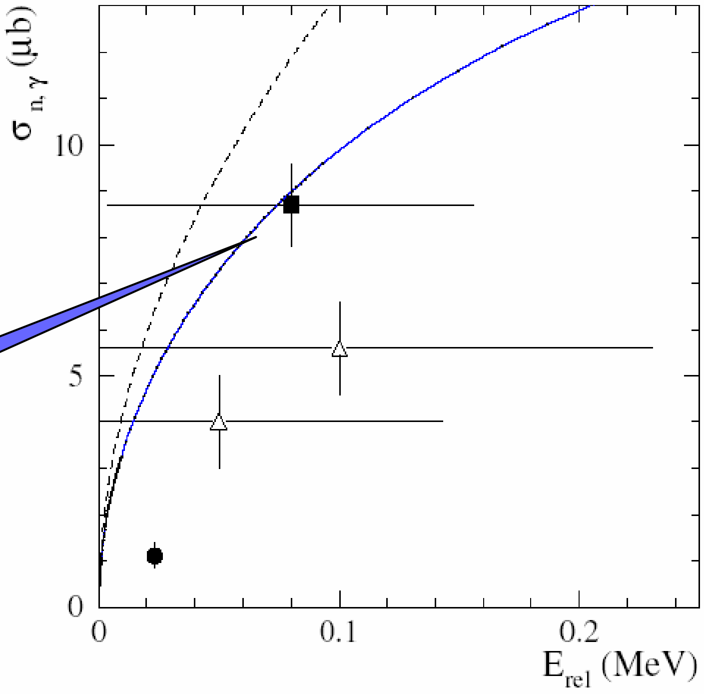
Coulomb breakup and Astrophysics
Example: The $^{14}C(n,\gamma)$ radiative capture reaction is important in the neutron-induced CNO cycles in the stellar evolution

Measurement of the inverse reaction using Coulomb breakup:



$$\sigma_{n,\gamma}(E_{\mathrm{rel}}) = \frac{(2j_a+1)}{(2j_b+1)(2j_n+1)}\frac{1}{\mu c^2}\frac{E_\gamma^2}{E_{\mathrm{rel}}}\sigma_{\gamma,n}$$





Problem: energy-resolution at present not sufficient to measure at very small relative energies

- ✔ Introduction: Physics, Experiments, Production
- ✔ At and beyond the drip line: knockout reactions

☛ **Dipole excitations of neutron-rich nuclei**

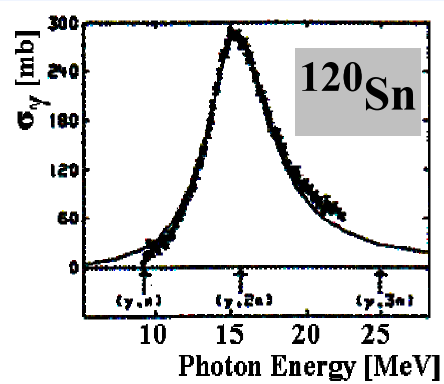
  - ✔ Coulomb breakup of halo nuclei
  - ☛ **Giant and Pygmy collective excitations**

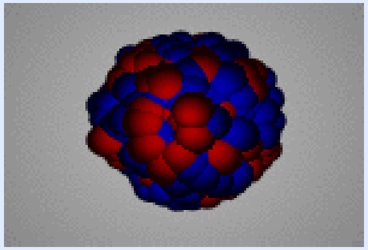
- Future Developments

The dipole response of neutron-rich nuclei

Stable nuclei:

100% of the E1 strength absorbed into the **Giant Dipole Resonance** (GDR)



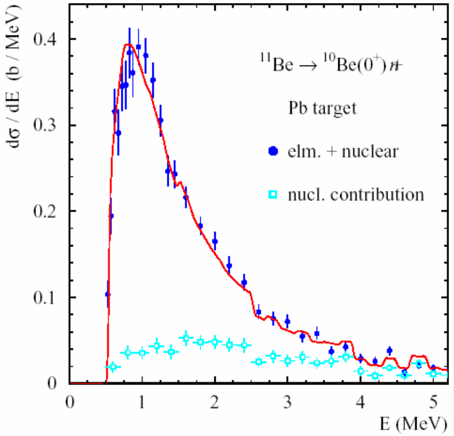


Neutron-Proton asymmetric nuclei: low-lying dipole strength

! threshold strength

non-resonant transitions

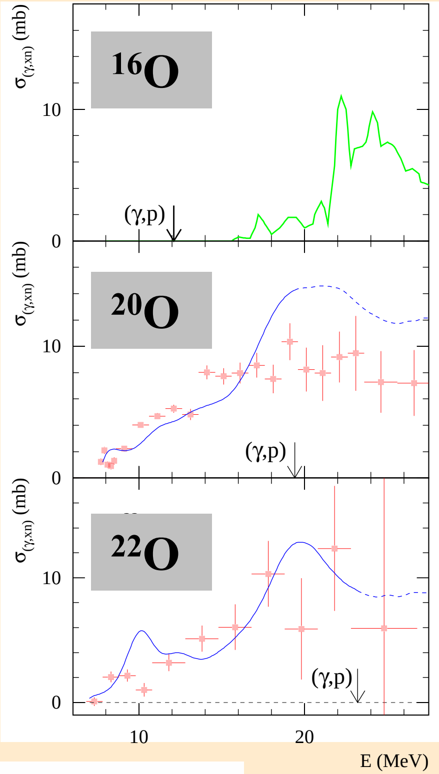
The one-neutron Halo **^{11}Be**



spectroscopic tool:

$$\frac{d\sigma}{dE^*}(I_c^\pi) = (\frac{16\pi^3}{9\hbar c})N_{E1}(E^*)\sum_{n\ell j} C^2S(I_c^\pi, n\ell j)$$
$$\times \sum_m |\langle \boldsymbol{q}|(Ze/A)rY_m^1|\phi_{n\ell j}(r)\rangle|^2.$$

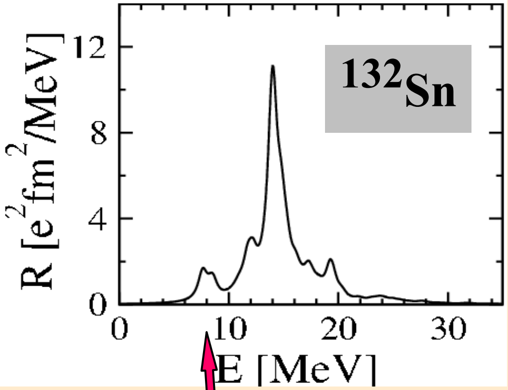
! strong fragmentation



? new collective soft dipole mode

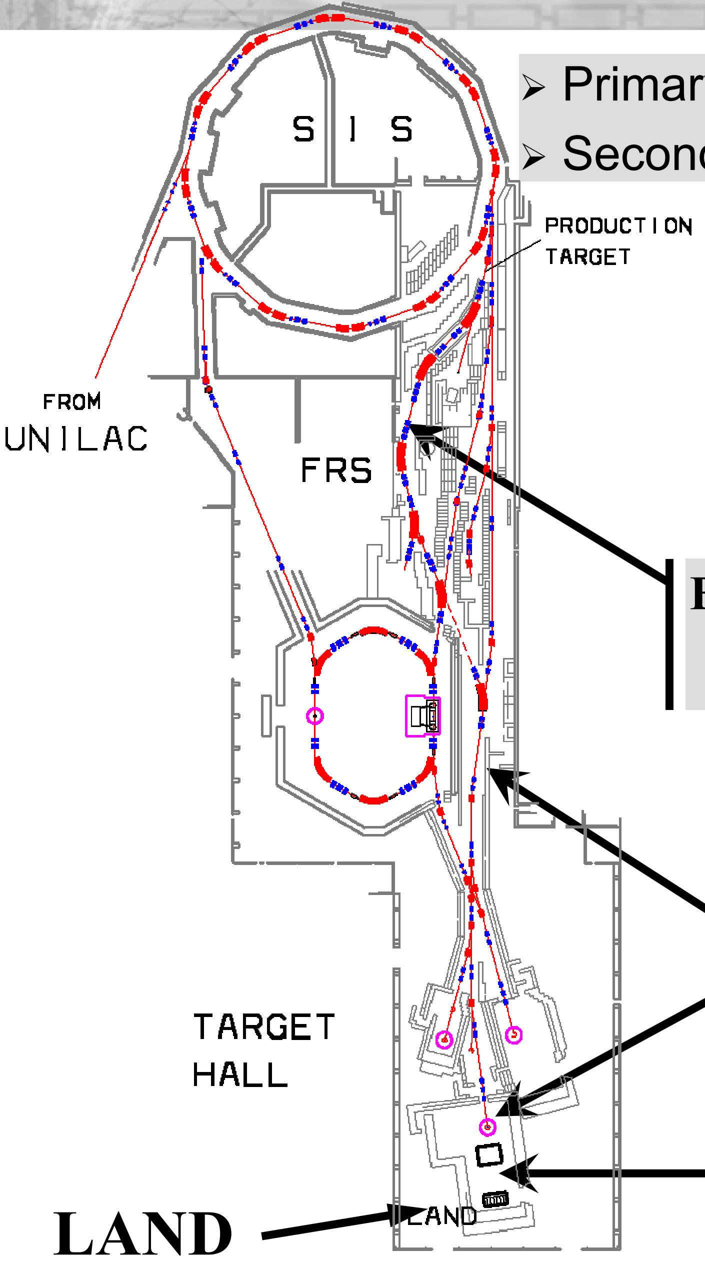
(Pygmy resonance)

Prediction: RMF
(N. Paar et al.)

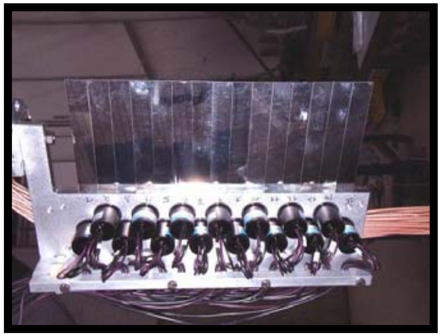


Experimental Approach: Production of (fission-)fragment beams

- Primary: $3*10^8$ ^{238}U/spill @550MeV/u
- Secondary (mixed): 50 ions ^{132}Sn/spill (~10/sec @500 MeV/u)



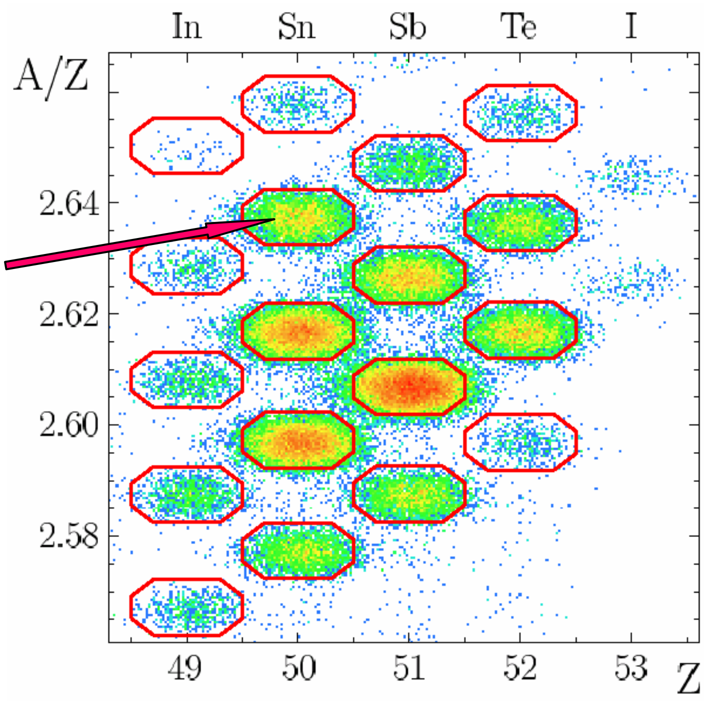
$$\frac{A}{Z} = \frac{e}{m_u c} \frac{B\rho}{\beta\gamma}$$



Bρ – from position at middle focal plane of the FRS

β – from TOF

Z – from ΔE

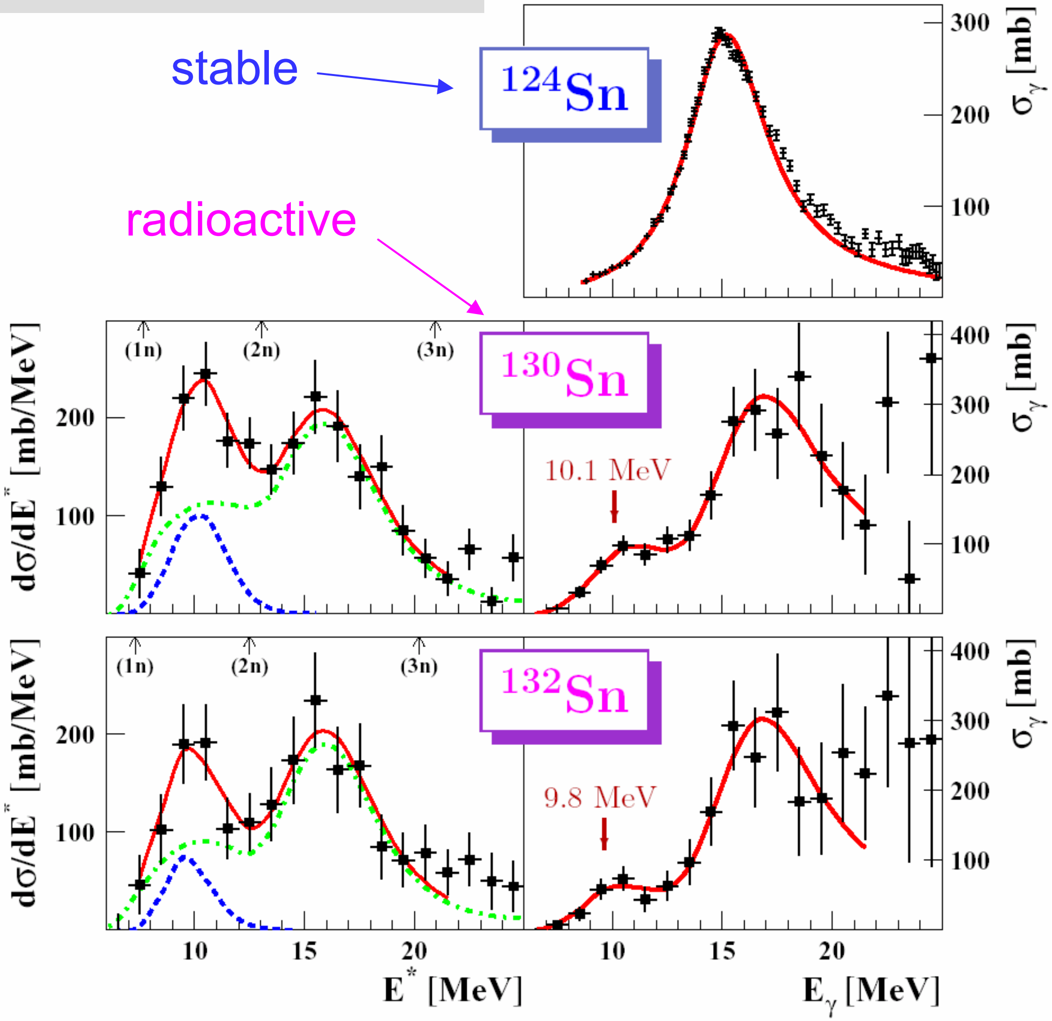


^{132}Sn

Dipole-strength distributions in neutron-rich Sn isotopes

Electromagnetic-excitation cross section

Photo-neutron cross section



A	PDR		GDR		
	E_{centr} [MeV]	sum rule fraction [%]	E_{centr} [MeV]	Γ [MeV]	sum rule fraction [%]
^{124}Sn	-	-	15.3	4.8	116
^{130}Sn	10.1 (0.7)	7.0 (3.0)	15.9 (0.5)	4.8 (1.8)	145 (19)
^{132}Sn	9.8 (0.7)	4.0 (3.1)	16.1 (0.8)	4.7 (2.2)	125 (32)

PDR

- located at 10 MeV
- exhausts a few % TRK sum rule
- in agreement with theory

GDR

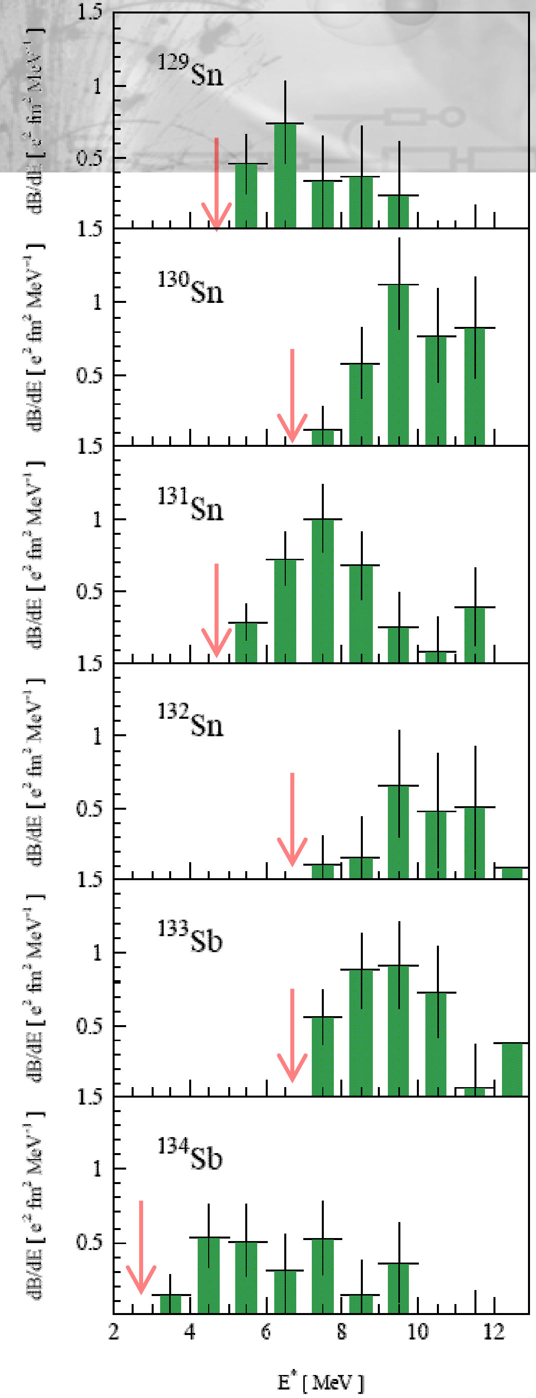
- no deviation from systematics

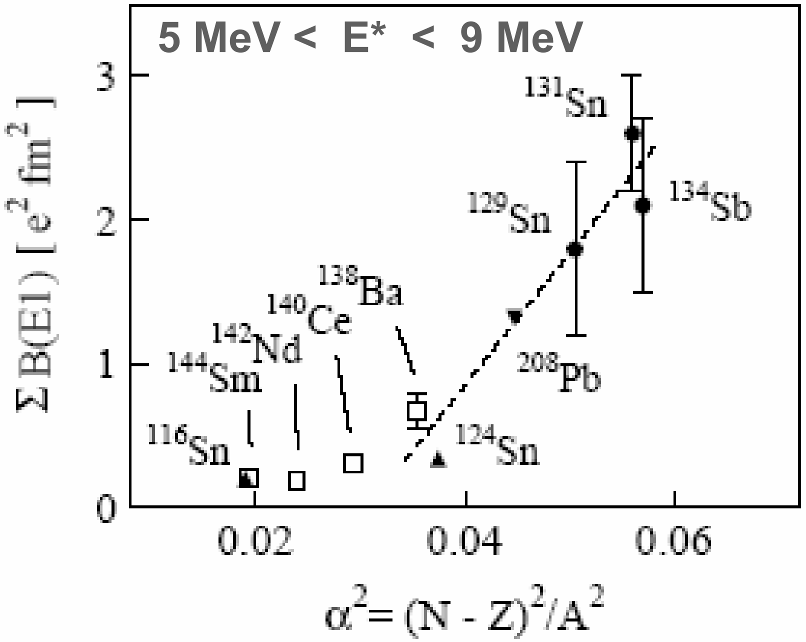
P. Adrich et al., PRL 95 (2005) 132501

Low-lying strength in ^{132}Sn mass neighborhood

odd nuclei allow extending (γ,n) measurements to lower excitation energies

→ comparison to (γ,γ') data for stable isotopes





A. Klimkiewicz et al, submitted to PRL

<u>*Stable nuclei, Photoabsorption, from:*</u>

A.Zilges et al., Phys.Lett. B 542,43 (2003)

S.Volz et al., Nucl.Phys. A 779, 1 (2006)

N. Ryezayeva et al., Phys.Rev.Lett. 89 (2002)

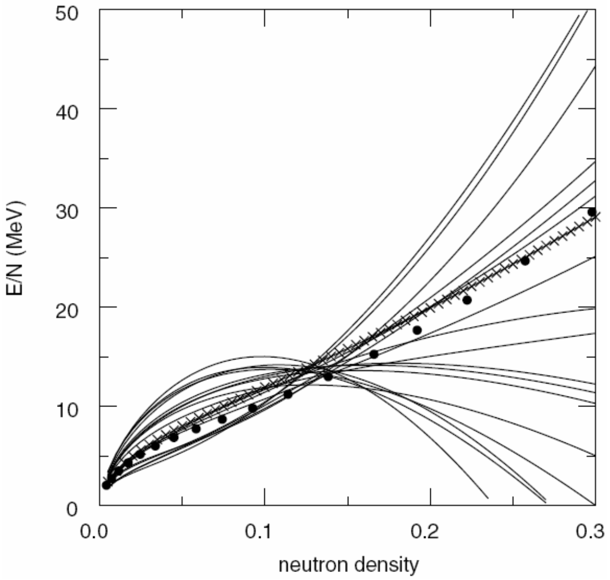
K. Govaert et al., Phys. Rev. C 57,2229 (1998)

Symmetry energy $S_2(\rho)$ and neutron skin in ^{208}Pb

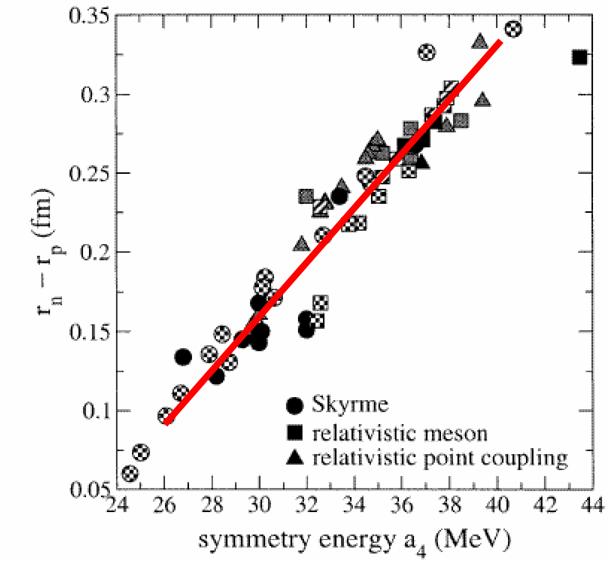
$$E(\rho,\alpha) = E(\rho,0) + \boxed{S_2(\rho)}\alpha^2 + O(\alpha^4)\,,\; \alpha = \frac{N-Z}{A}$$

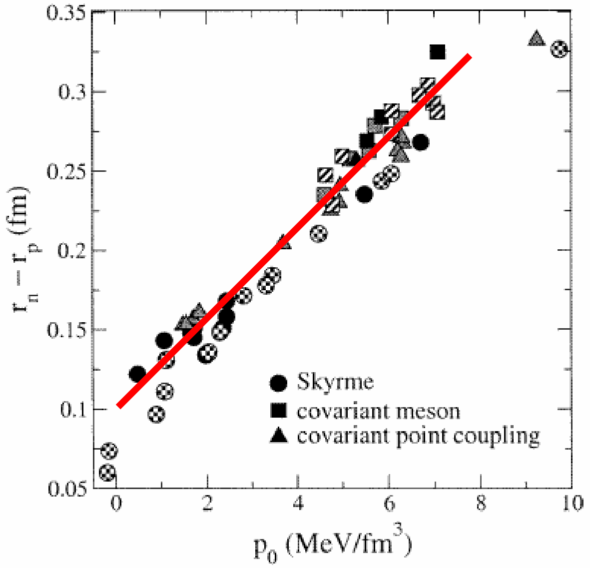
$$S_2(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\alpha)}{\partial \alpha^2}\bigg|_{\alpha=0} =$$

$$= a_4 + \frac{p_0}{\rho_0^2}(\rho-\rho_0) + \frac{\Delta K_0}{18\rho_0^2}(\rho-\rho_0)^2 + \ldots$$



Alex Brown,
PRL 85 (2000) 5296





R.J.Furnstahl
NPA 706(2002)85-110

- strong linear correlation between neutron skin thickness and parameters **a_4, p_0**

Symmetry energy and neutron skin form dipole strength

Theory: Precise knowledge of neutron-skin thickness could
constrain the density dependence of S(ρ)

Work Hypothesis: **Pygmy-Strength (since related to skin)**
should do the same job,
but, experimentally, is accessed much easier !

Inspired by recent article of Piekarewicz *(Phys. Rev. C 73 , 044325 (2006))*

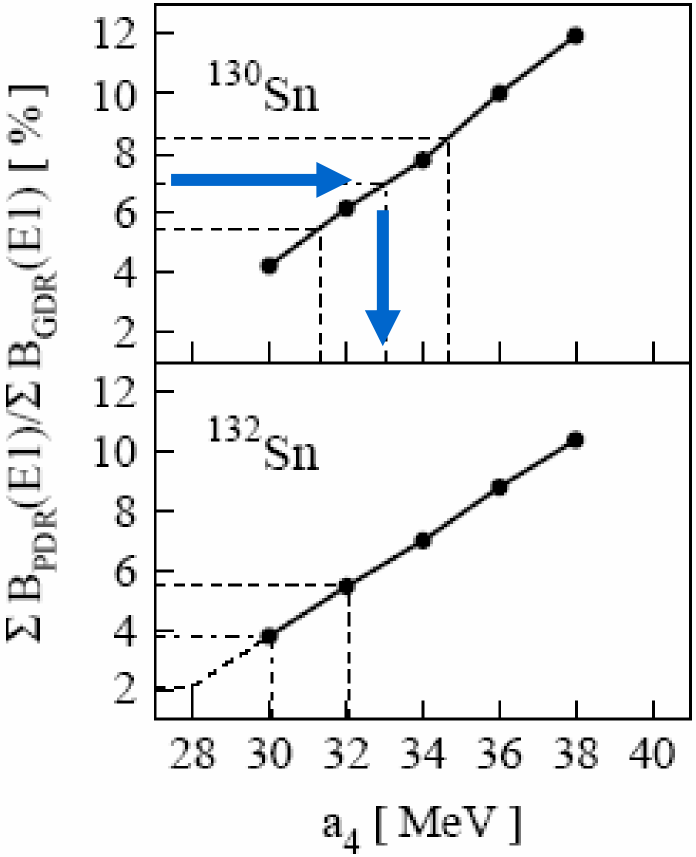
Here:

Quantitative attempt by means of RHB + RQRPA,

(density-dependent meson-exchange DD-ME)

Paar, Vretenar, Ring et al. (Phys. Rev. C67, 34312 (2003))

PDR strength versus a_4, p_o

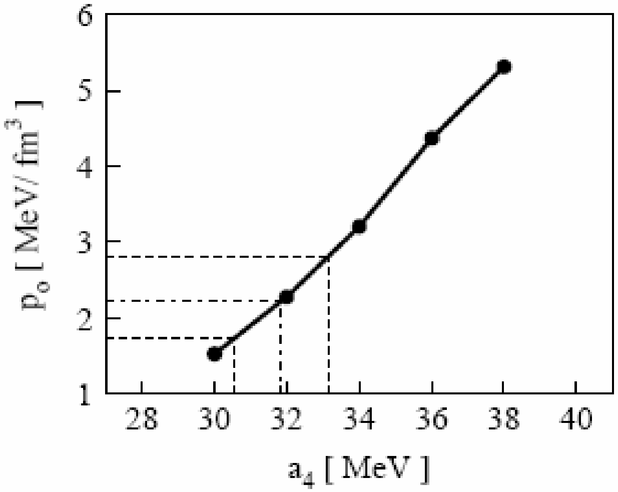


RQRPA – DD-ME

N. Paar et al.

Result (*averaged ^{130,132}Sn) :*

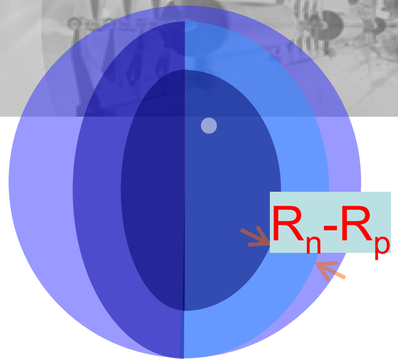
a_4 = 32.0 ± 1.8 MeV

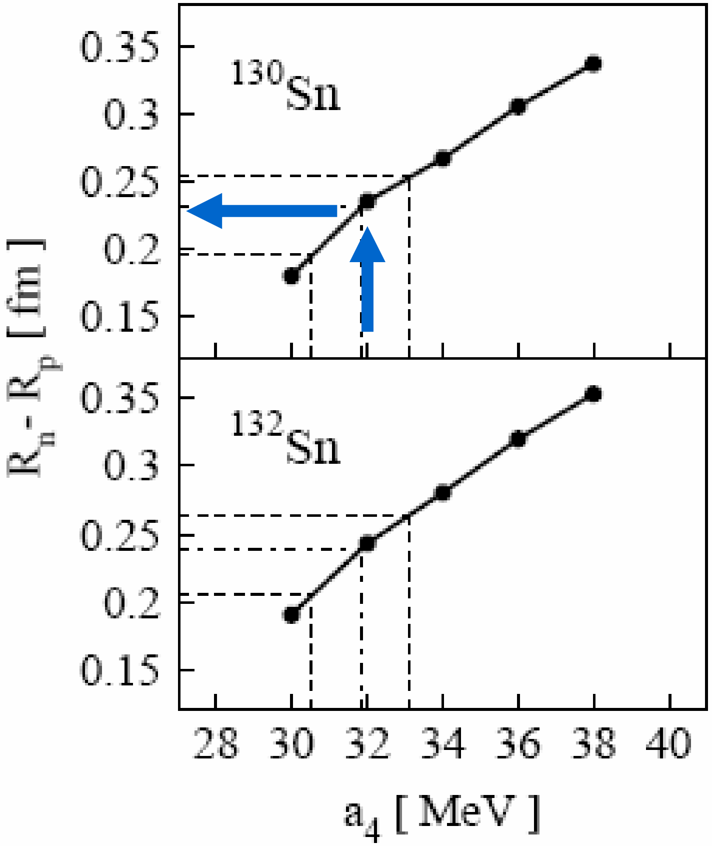


p_o = 2.3 ± 0.8 MeV/fm^3

S(ρ) : moderate stiffness

Neutron skin thickness





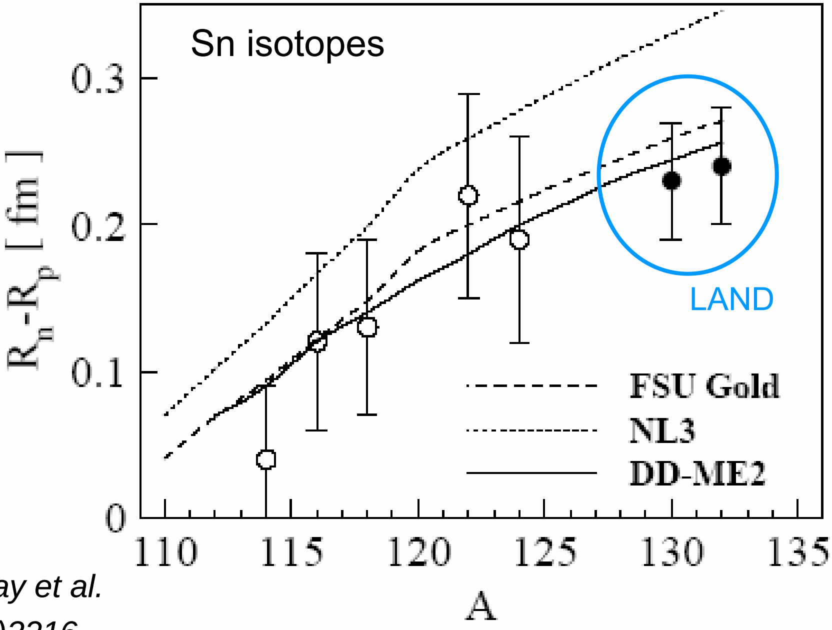
A. Klimkiewicz, N. Paar, et al,

submitted to PRL

R_n – R_p :

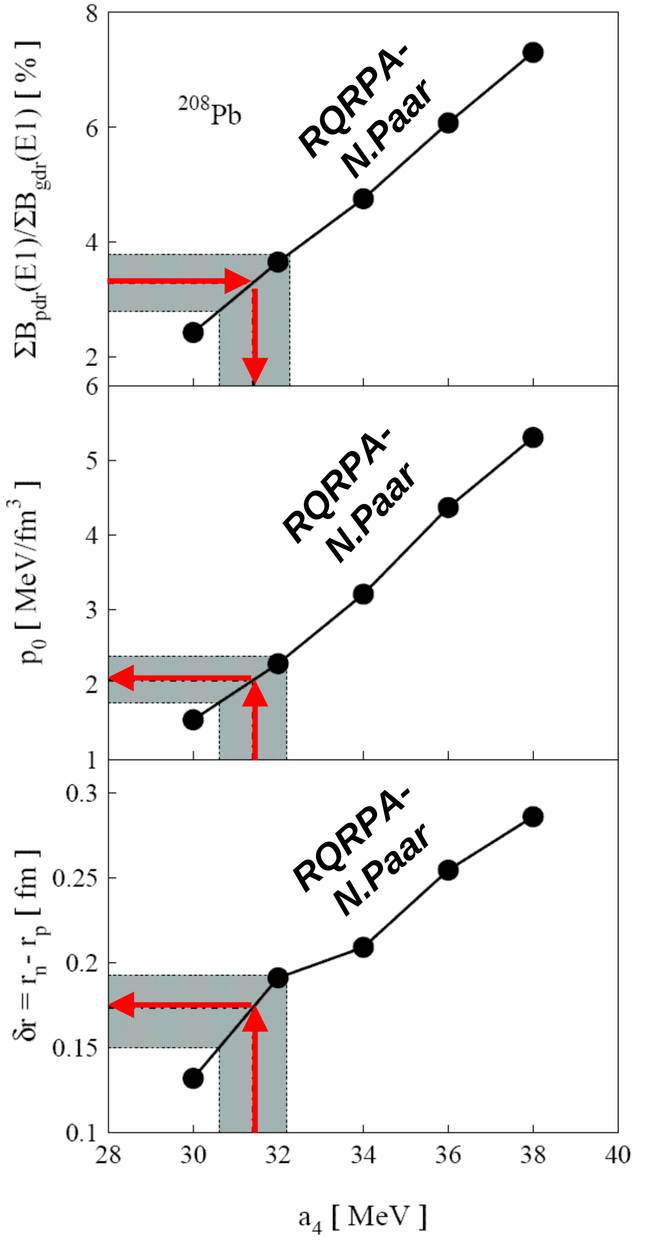
^{130}Sn: 0.23 ± 0.04 fm

^{132}Sn: 0.24 ± 0.04 fm



A.Krasznahorkay et al.
PRL 82(1999)3216

^{208}Pb analysis



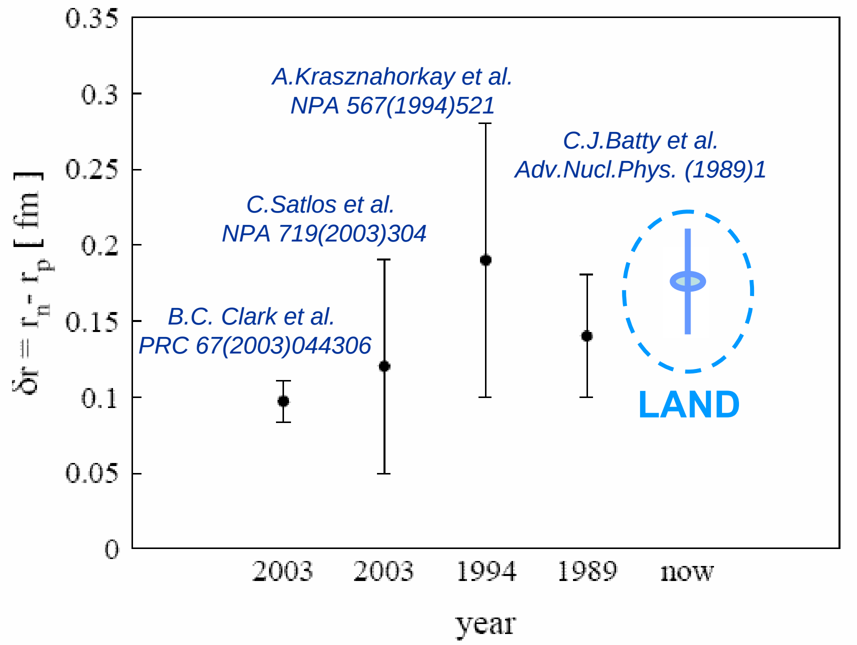
$\Sigma B_{pdr}(E1)=1.98\ e^2\ fm^2$

from N.Ryezayeva et al., PRL 89(2002)272501

$\Sigma B_{gdr}(E1)=60.8\ e^2\ fm^2$

from A.Veyssiere et al.,NPA 159(1970)561

$$\boxed{R_n - R_p = 0.18 \pm 0.035\ \text{fm}}$$



Conclusion

- Low-lying dipole strength observed in light and medium-mass neutron-rich nuclei
- Threshold strength (halo nuclei) established as spectroscopic tool
- Peak-like structure below the GDR in ^{130,132}Sn at about 10 MeV excitation energy exhausting about 5% of the energy-weighted sum rule
- Parameters of GDR in agreement with systematic trends derived from stable nuclei
- Symmetry energy and neutron-skin thickness from dipole strength: a first attempt

Outlook:

- ***Systematic measurements*** of dipole strength in neutron-proton asymmetric nuclei
- Theory+experiment: Relation of low-lying dipole strength to ***symmetry energy and neutron skin***
- ***Decay characteristics*** (e.g., γ decay branch)
  (γ,γ') in ^{68}Ni (RISING), ***(γ,n)*** with LAND setup
- ***Monopole and quadrupole strength:***

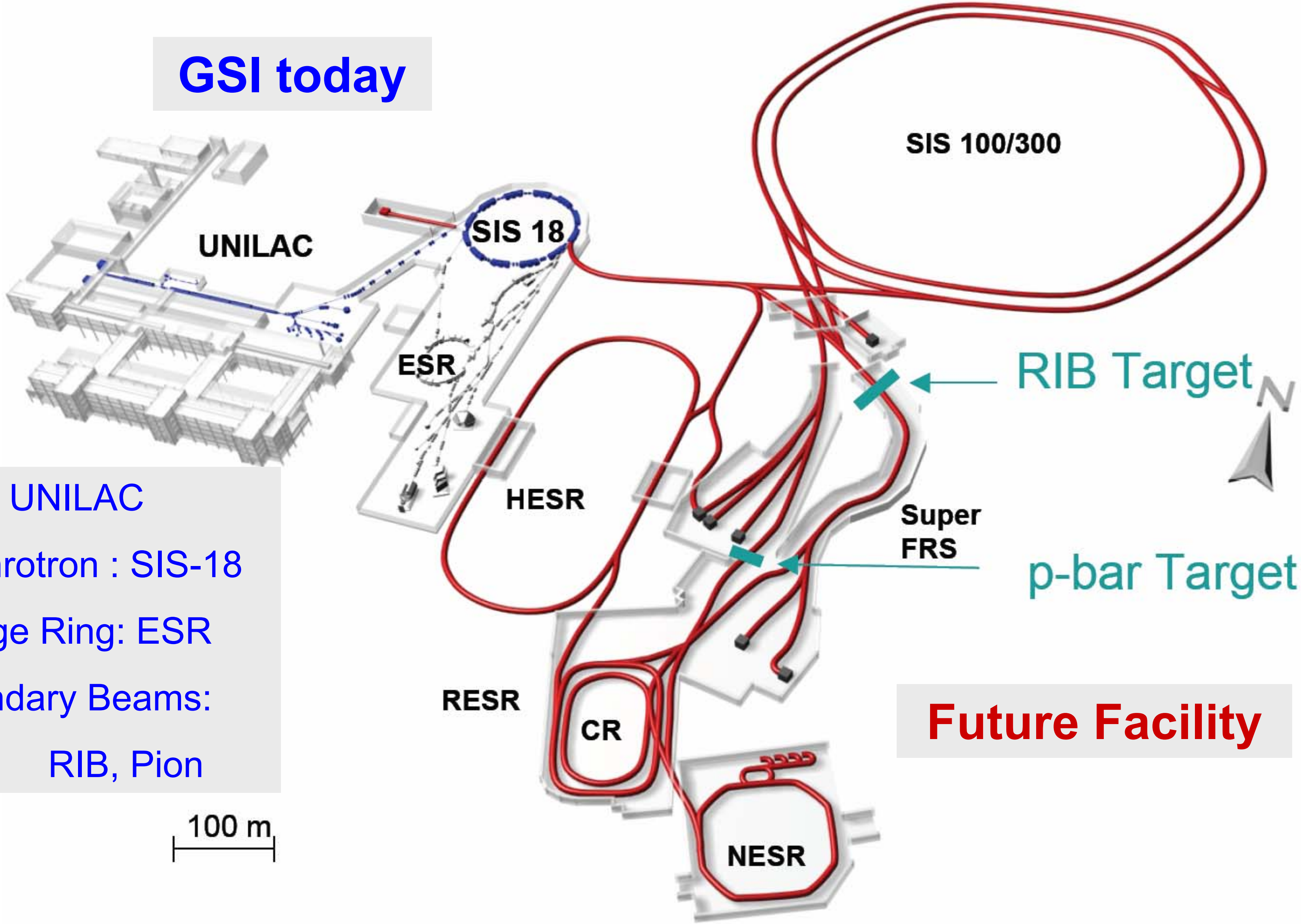
  internal gas target in a storage ring (GSI, FAIR), electron-heavy-ion collider (FAIR)

- ✔ Introduction: Physics, Experiments, Production
- ✔ At and beyond the drip line: knockout reactions
- ✔ Dipole excitations of neutron-rich nuclei
  - Coulomb breakup of halo nuclei
  - Giant and Pygmy collective excitations

☛ **Future Developments: Experimental Program at FAIR**

FAIR – Facility for Antiproton and Ion Research

GSI today



Linac: UNILAC

Synchrotron : SIS-18

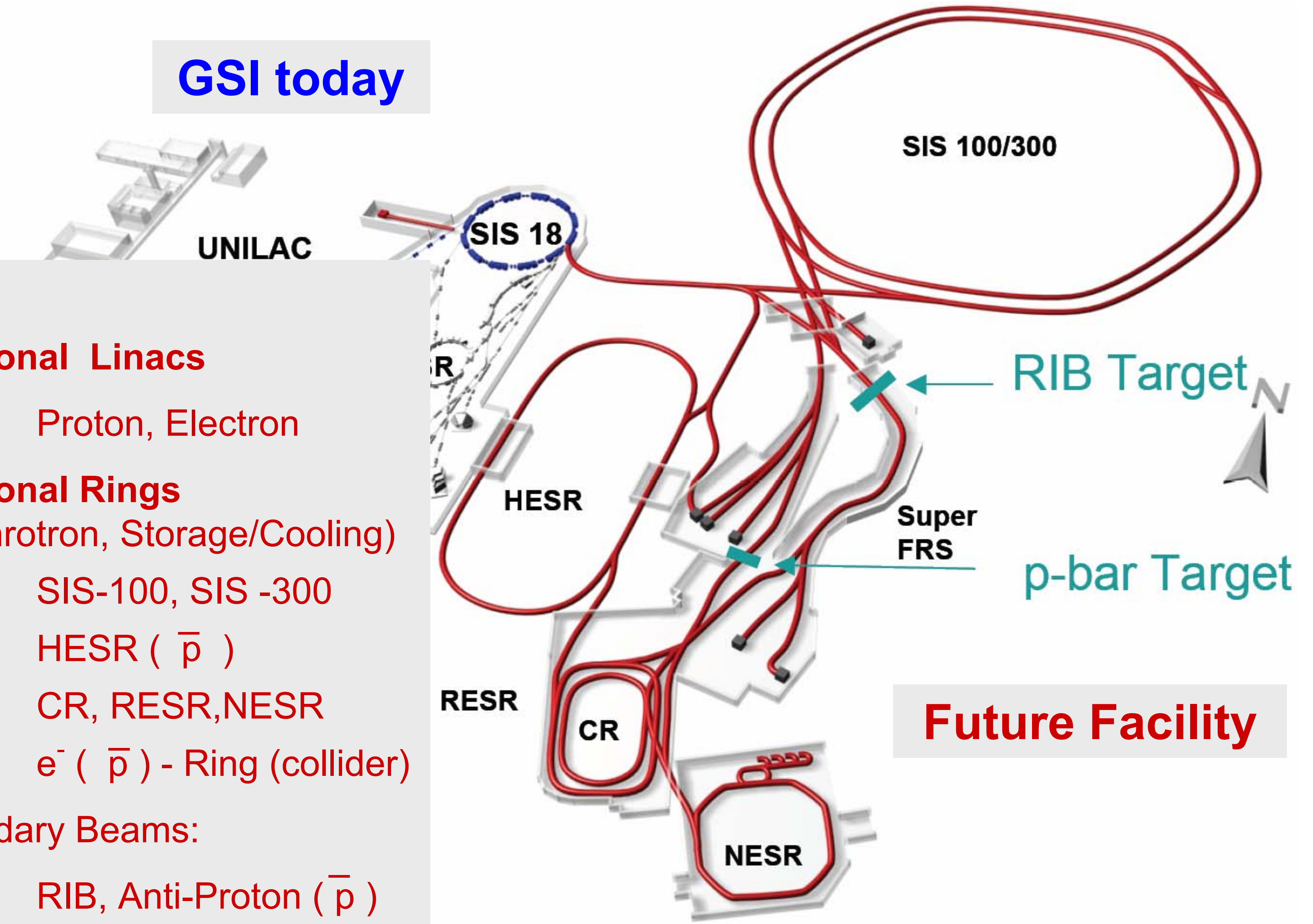
Storage Ring: ESR

Secondary Beams:

RIB, Pion

Future Facility

FAIR – Facility for Antiproton and Ion Research



FAIR

Additional Linacs

Proton, Electron

Additional Rings

(Synchrotron, Storage/Cooling)

SIS-100, SIS -300

HESR ($\bar{p}$)

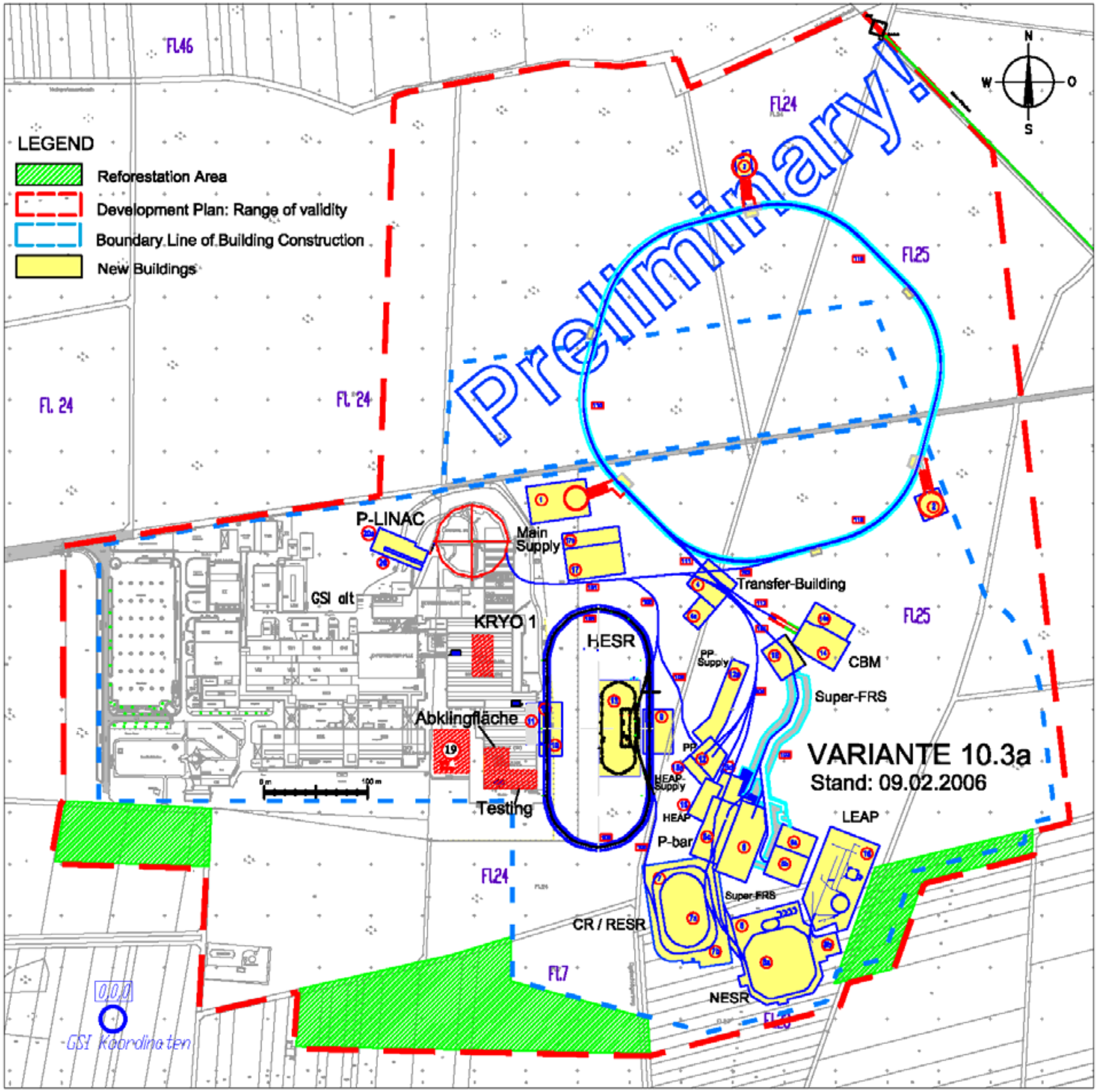
CR, RESR,NESR

e^- ($\bar{p}$) - Ring (collider)

Secondary Beams:

RIB, Anti-Proton ($\bar{p}$)

Topology of FAIR (FBTR 03/2006)



1	Extraction Building
2	Injection Building
3	Emergency Exit
4	Transfer Building
4a	Transfer - Supply
6	Super - FRS
6a	Super - FRS Supply
6b	Super - FRS LE - Branch
6c	P-bar - Target
6d	P-bar - Target Supply
7	CR / RESR
7a	CR / RESR Supply
7b	CR / RESR High Building
8	NESR
8a	NESR Supply
8b	NESR - Preparation
9	HESR PANDA Detector
10	HESR - Cooler
10a	HESR - Cooler Tower
11	HESR Supply
12	PP
12a	PP/HEBT Supply & LASER
13	HESR - COSY
14	NC (CBM)
14a	NC (CBM) Supply
15	HEAP
15a	HEAP Supply
16	LEAP Supply
17	Main Supply Building
17a	Compressor Building
18	Super - FRS Targethalle
19	Office Building
20	P - Linac
20a	P - Linac Supply

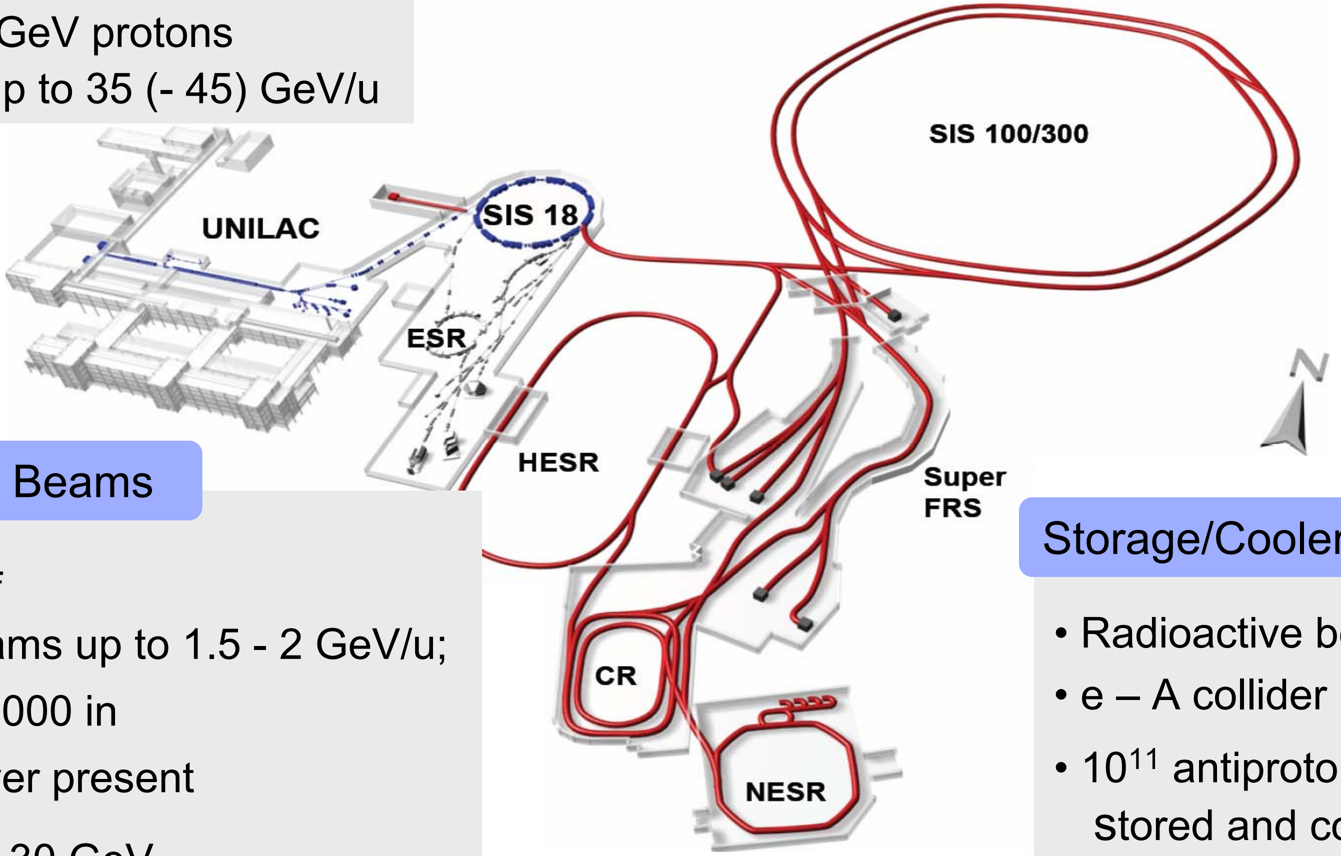
101	SIS18 - Transfer
102	Transfer Injection SIS100
103	Super - FRS
104	Transfer SIS100/300 - Exp.
105	Transfer SIS18 - PP
106	Transfer CR/RESR - HESR
107	HESR - Injection
108	HESR
110	SIS100/300 Tunnel
111	Extraktion SIS100/300
112	Transfer CBM-Cave

FAIR characteristics

Primary Beams

- 10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000
  over present in intensity
- 2(4)x10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 35 (- 45) GeV/u

High intensities – High precision



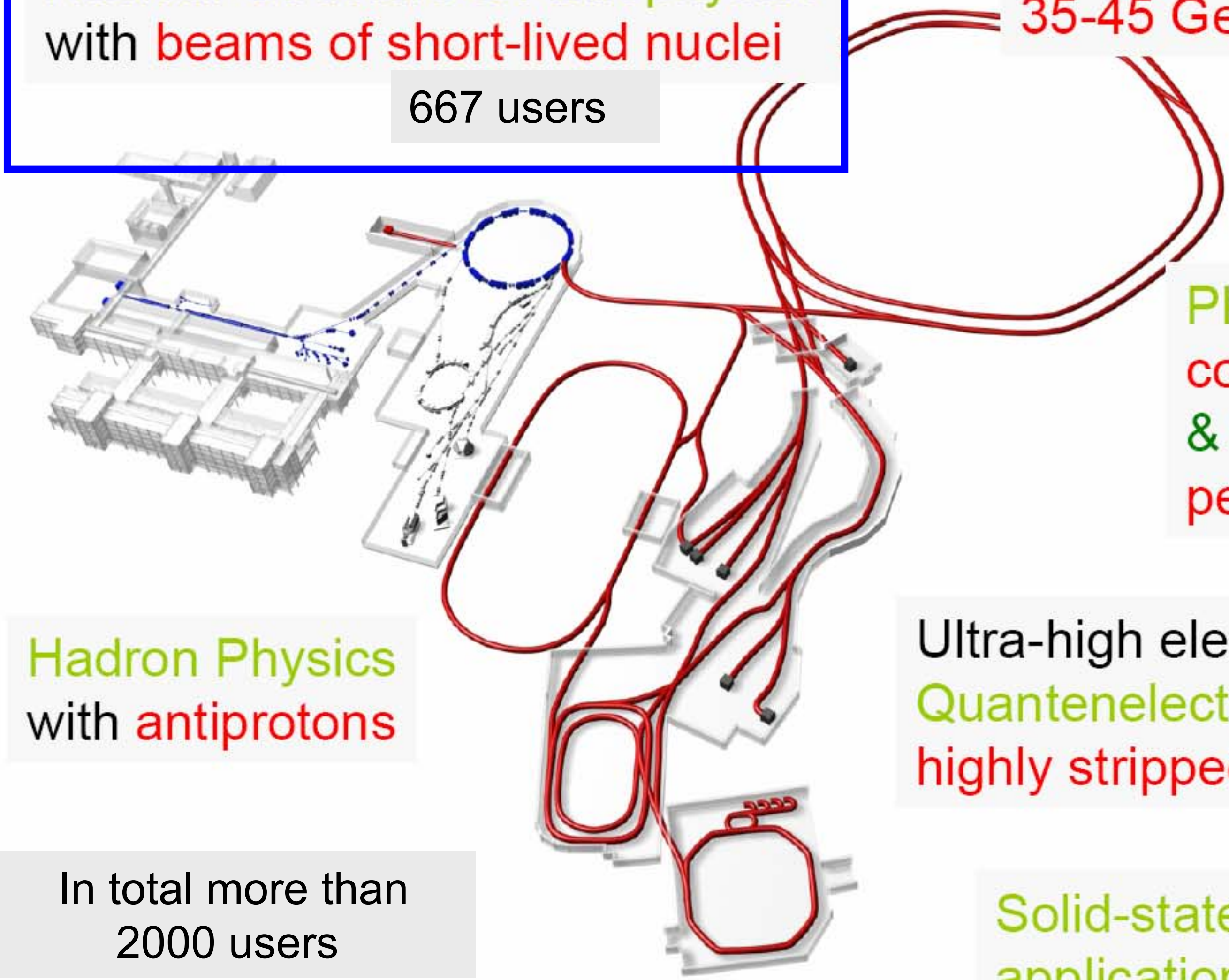
Secondary Beams

- 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/Cooler Rings

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

Research fields at FAIR



Nuclear Structure & Astrophysics with beams of short-lived nuclei

667 users

Nuclear Matter Physics with 35-45 GeV/u HI beams

Plasma Physics with compressed ion beams & high-intensity petawatt-laser

Hadron Physics with antiprotons

Ultra-high electro-magnetic fields & Quantenelectrodynamics with highly stripped ions and antimatter

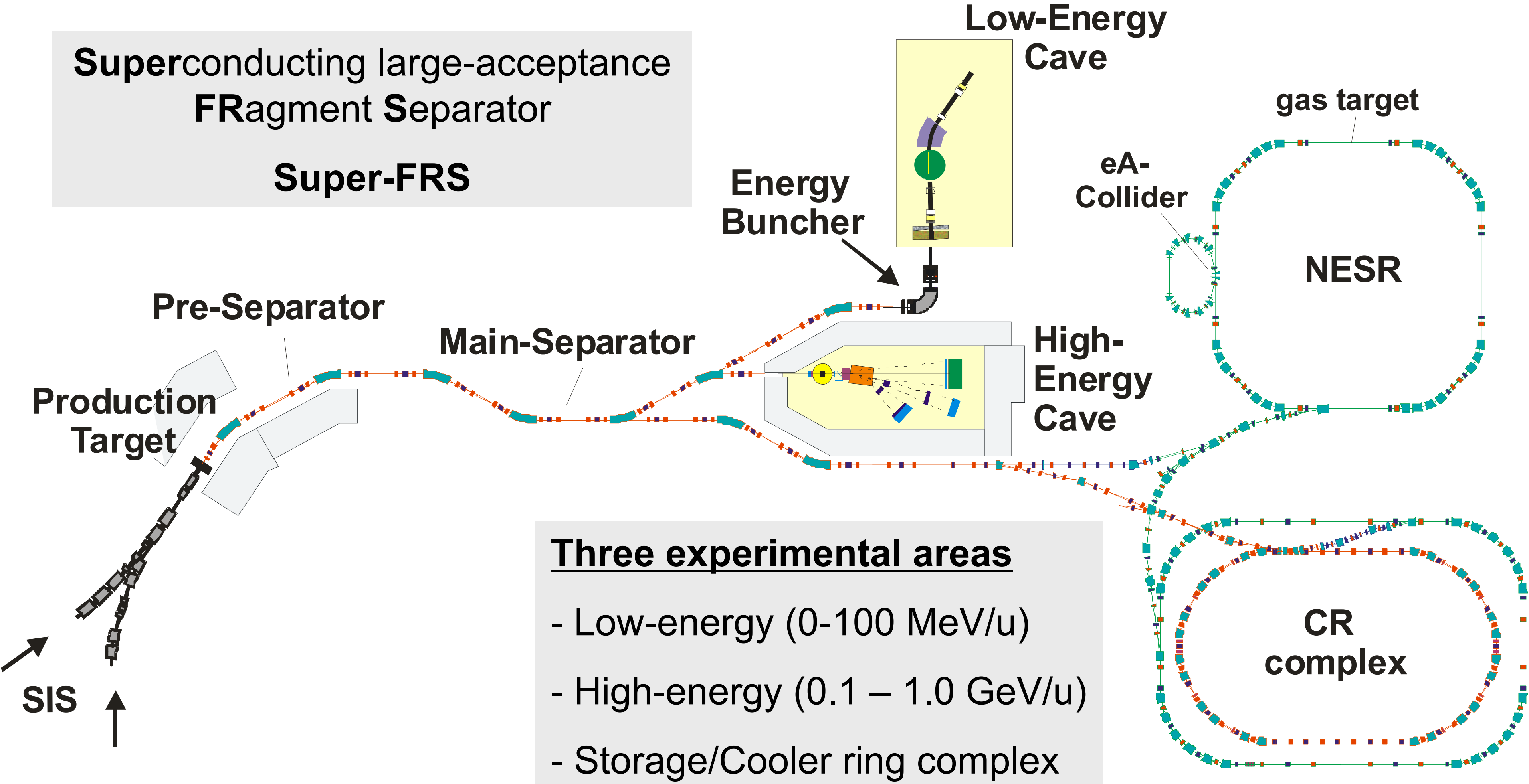
In total more than 2000 users

Solid-state and biological applications with ion beams

The rare-isotope beam facility NuSTAR

Superconducting large-acceptance **FR**agment **S**eparator

Super-FRS

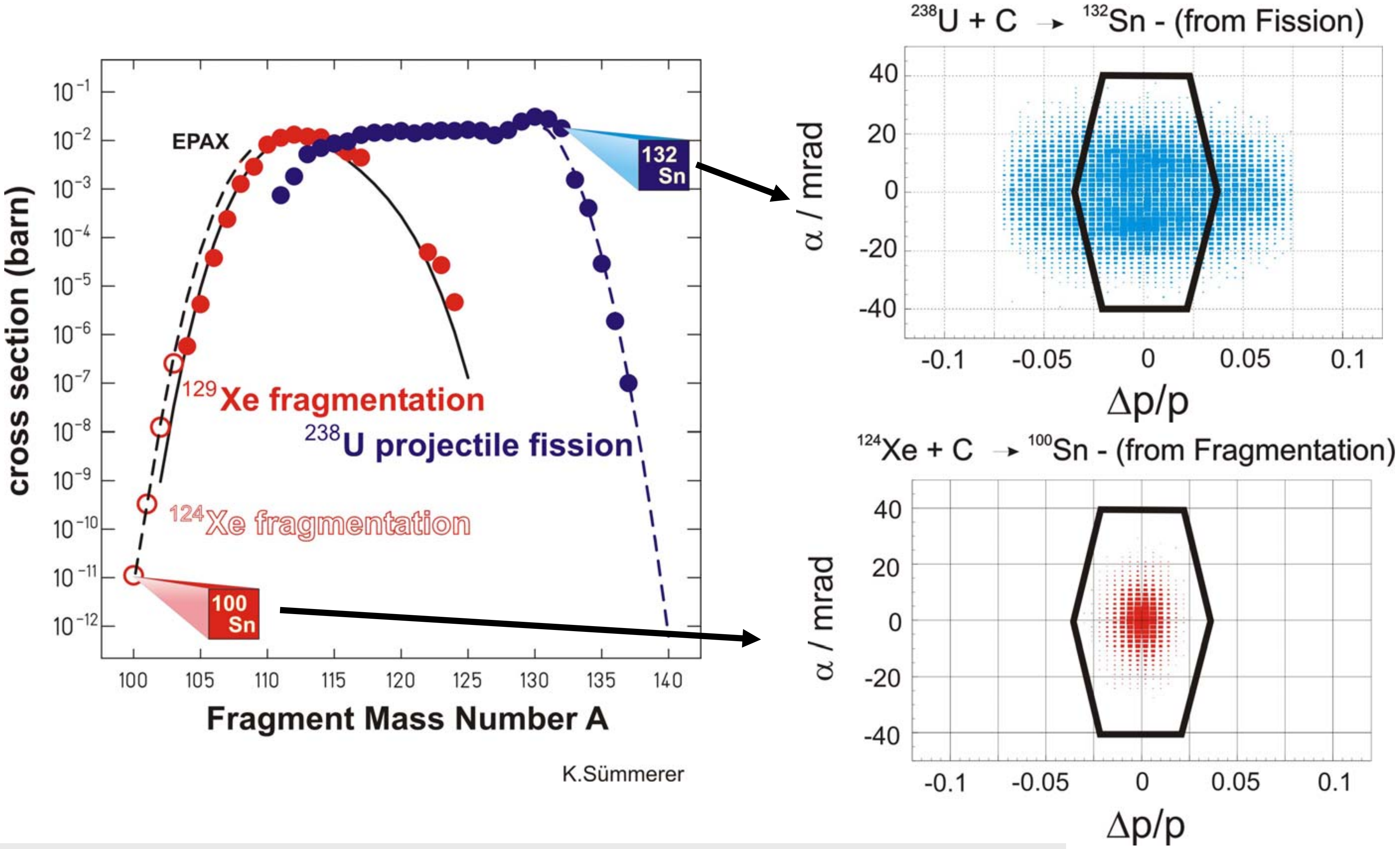


Three experimental areas

- Low-energy (0-100 MeV/u)
- High-energy (0.1 – 1.0 GeV/u)
- Storage/Cooler ring complex

NuSTAR - Nuclear Structure, Astrophysics, and Reactions

Production of radioactive beams by fragmentation and fission



K.Sümmerer

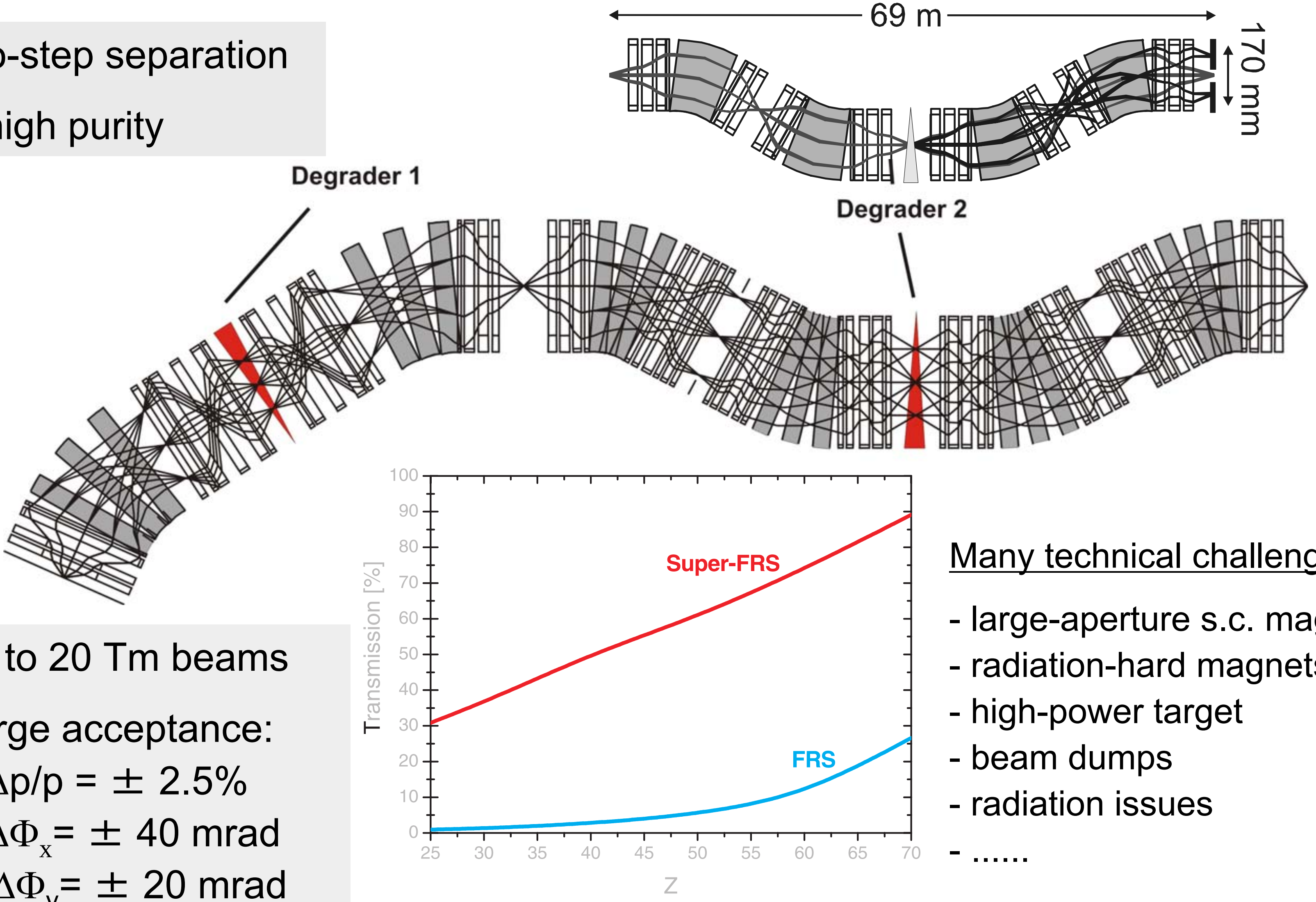
Large acceptance required for separation of fission fragments

Martin Winkler

Superconducting Fragment Separator Super-FRS

Two-step separation

→ high purity



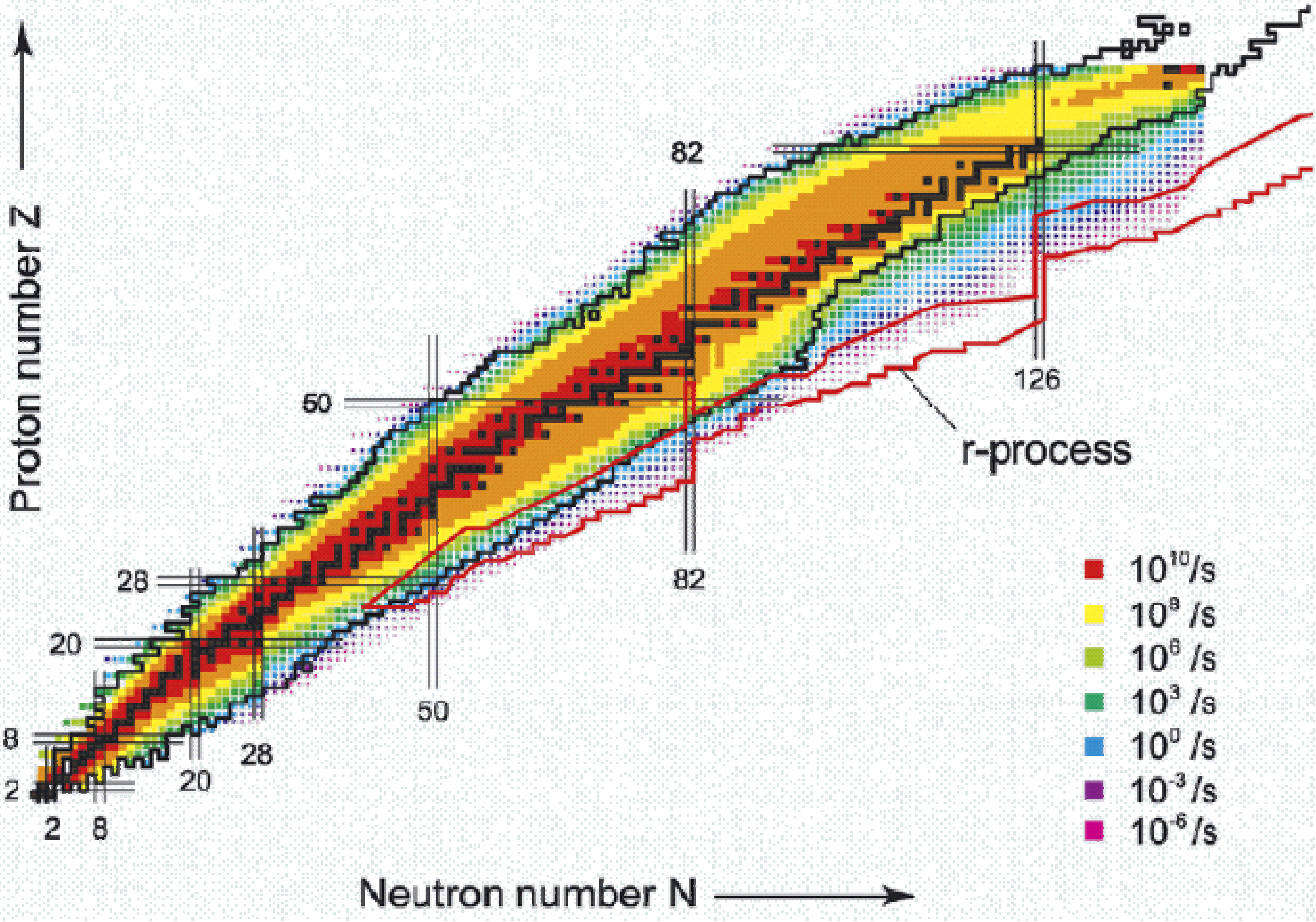
- up to 20 Tm beams
- Large acceptance:
  - $\Delta p/p = \pm\ 2.5\%$
  - $\Delta\Phi_x = \pm\ 40$ mrad
  - $\Delta\Phi_y = \pm\ 20$ mrad

Many technical challenges:

- large-aperture s.c. magnets
- radiation-hard magnets
- high-power target
- beam dumps
- radiation issues
- ......

→ High transmission for fission fragment (intensity gain by a factor of ~10)

RIB intensities after Super-FRS



Accepted NuSTAR Experiments at FAIR

- 2004/2005: LoIs and Proposals submitted
- early 2006: Technical Proposals submitted

Formation of the
NuSTAR collaboration

Evaluation by NuSTAR PAC

667 users

1.) Low Energy Branch (LEB)

- High-resolution In-Flight Spectroscopy (HISPEC)/ Decay Spectroscopy with Implanted Ion Beams (DESPEC)	Zs.Podolyak + B. Rubio	Surrey Valencia
- Precision Measurements of very short-lived Nuclei using an Advanced Trapping System for highly-charged Ions (MATS)	K.Blaum	Mainz
- LASER Spectroscopy for the Study of Nuclear Properties (LASPEC)	P. Campbell	Manchester
- Neutron Capture Measurements (NCAP)	M.Heil	GSI

2.) High Energy Branch (R3B)

- A Universal Setup for Kinematical Complete Measurements of Reactions with Relativistic Radioactive Beams (R3B)	T. Aumann	GSI

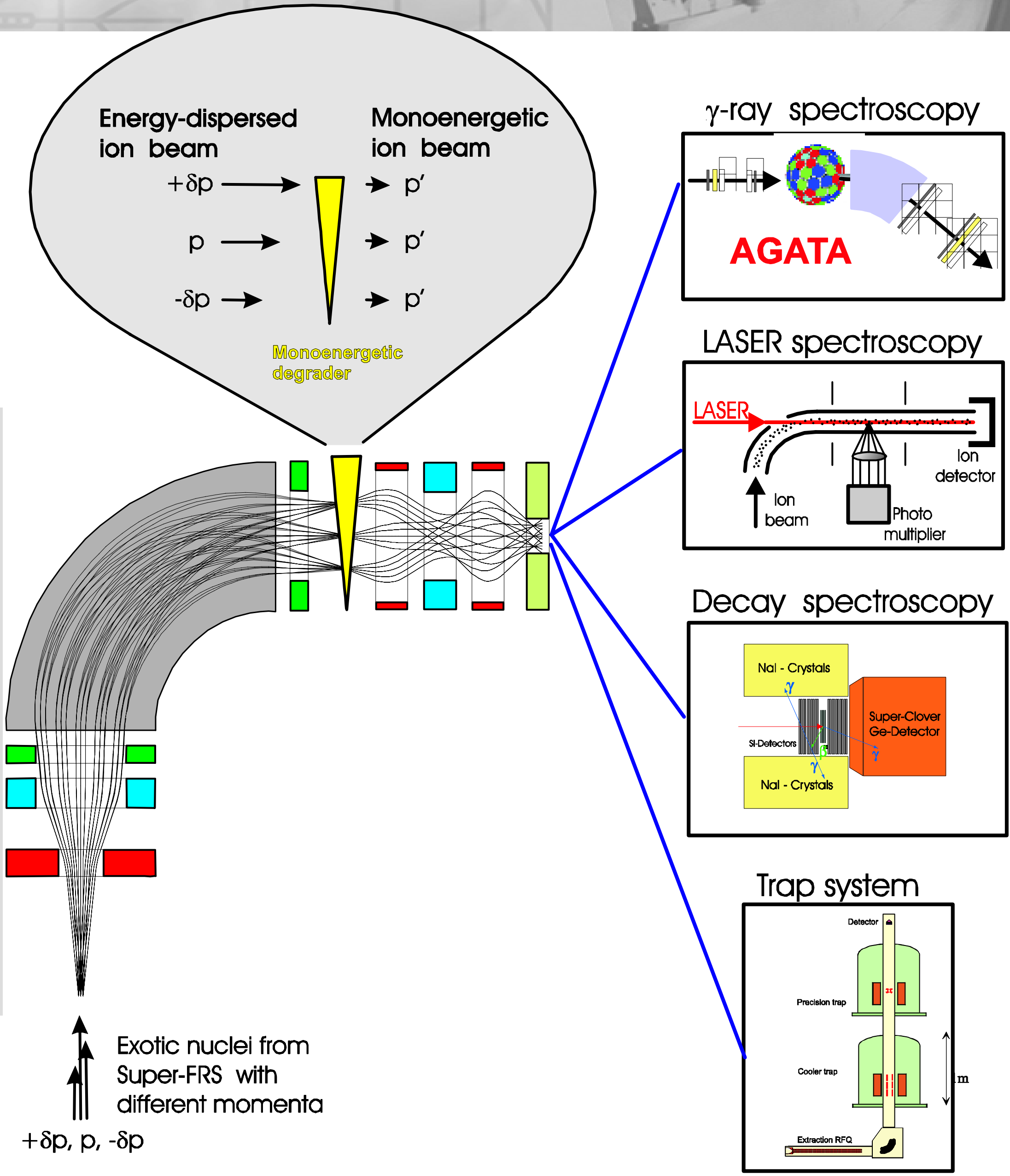
3.) Ring Branch (STORIB)

- Study of Isomeric Beams, Lifetimes and Masses (ILIMA)	Y .Novikov	SPNPI
- Exotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring (EXL)	M. Chartier	Liverpool
- Electron-Ion Scattering in a Storage Ring (e-A Collider) (ELISe)	H. Simon	GSI
- Antiproton-Ion Collider: A Tool for the Measurement of Neutron and Proton rmsradii of Stable and Radioactive Nuclei (AIC)	R. Krücken	TUM

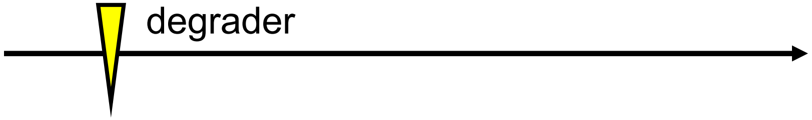
Low-energy radioactive beams

Energy-bunched
slowed-down and
stopped beams

- Decay spectroscopy (DESPEC)
- In-flight γ spectroscopy (3 – 100 MeV/u) (HISPEC)
- Laser spectroscopy (LASPEC)
- Ion traps (MATS)
- Neutron capture (NCAP)

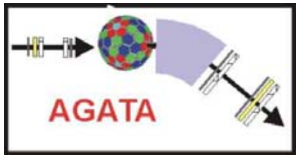


Experiments at the LEB

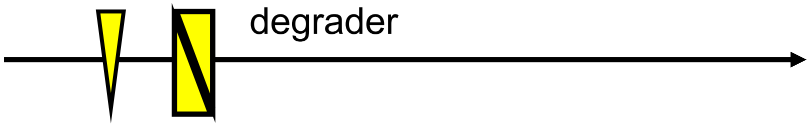


Monoenergetic
degrader

Slow beams
(100...3 MeV/u)

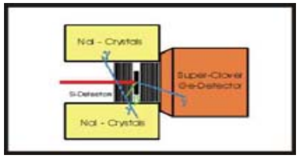


in-beam γ-ray
spectroscopy
with AGATA

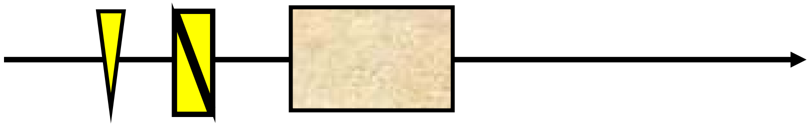


Monoenergetic + variable
degrader

Stopped beams
(~ 25meV)

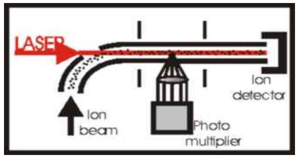


α, β, γ -decay
spectroscopy
isomers,
very exotic nuclei



He-filled
ion catcher

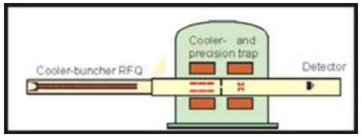
ISOL-type beams
(~10...100 keV)



LASER
spectroscopy
moments, radii

EBIS + analyzer

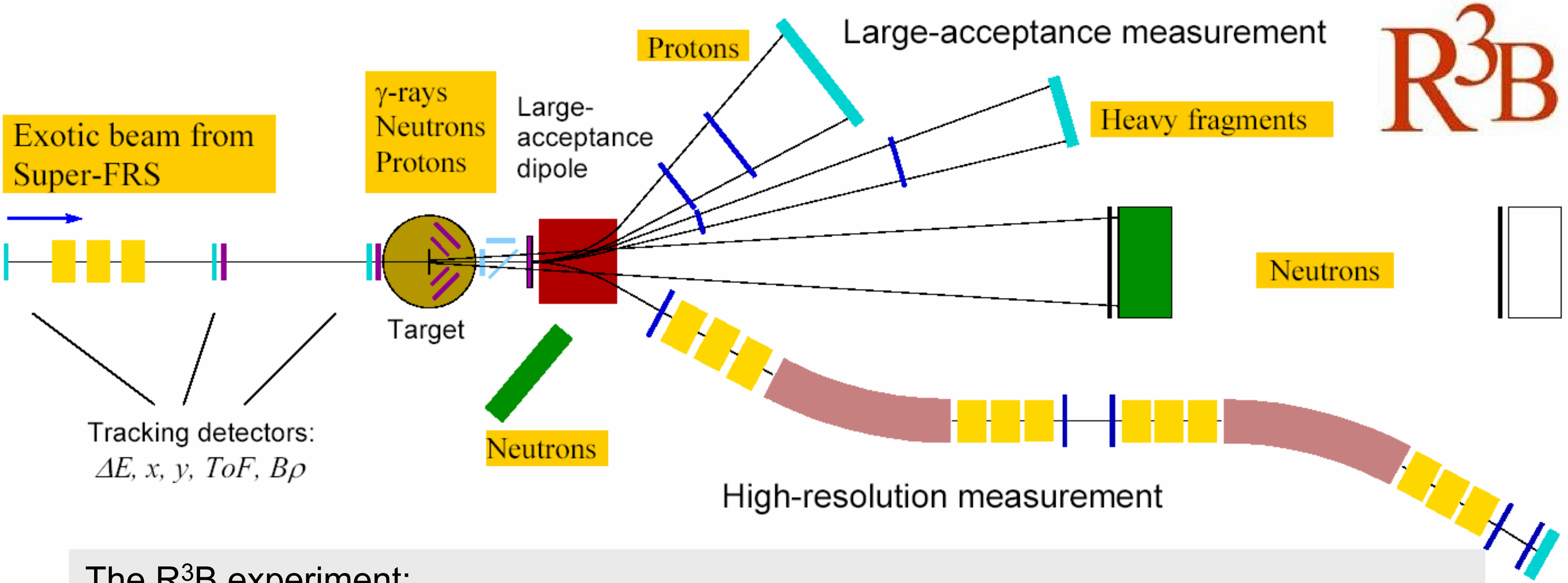
Highly-
charged ions



in-trap ex-
periments
precision mass
mesurements

A universal setup for kinematical complete measurements of

Reactions with Relativistic Radioactive Beams

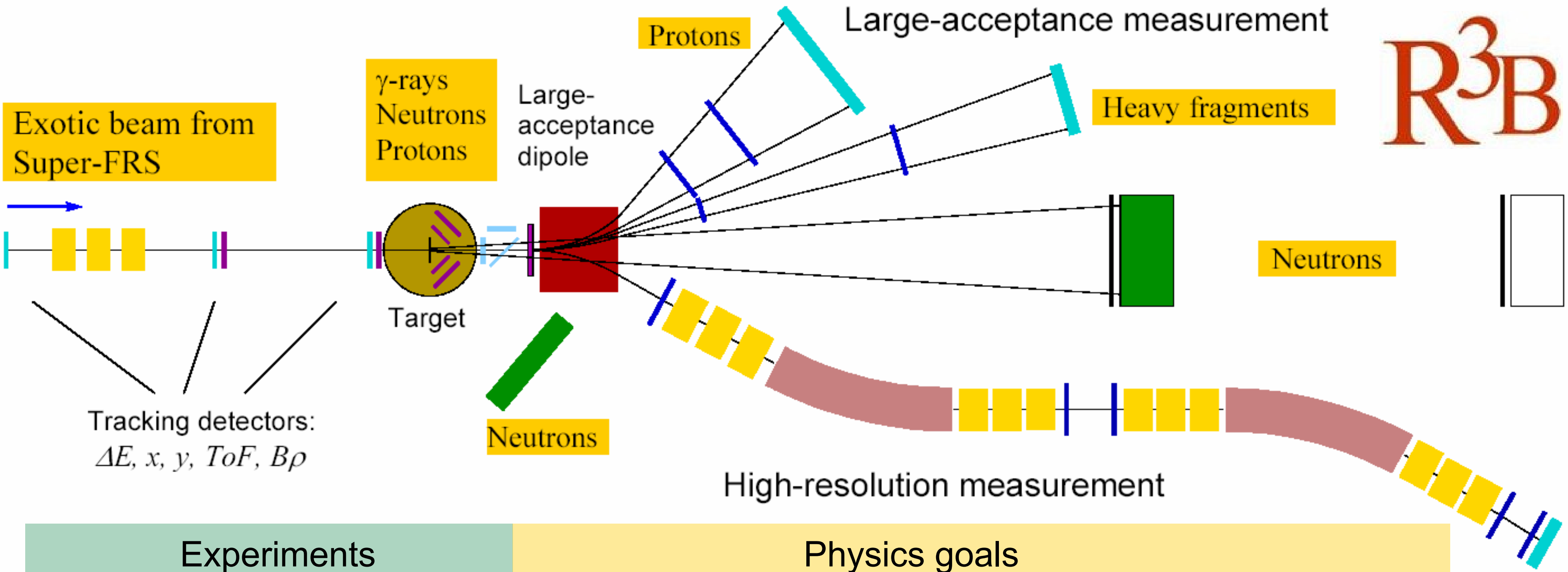


The R^{3}B experiment:

- identification and beam "cooling" (tracking and momentum measurement, $\Delta p/p \sim 10^{-4}$)
- exclusive measurement of the final state:
  - identification and momentum analysis of fragments (large acceptance mode: $\Delta p/p \sim 10^{-3}$, high-resolution mode: $\Delta p/p \sim 10^{-4}$)
  - coincident measurement of neutrons, protons, gamma-rays, light recoil particles
- applicable to a wide class of reactions

A universal setup for kinematical complete measurements of

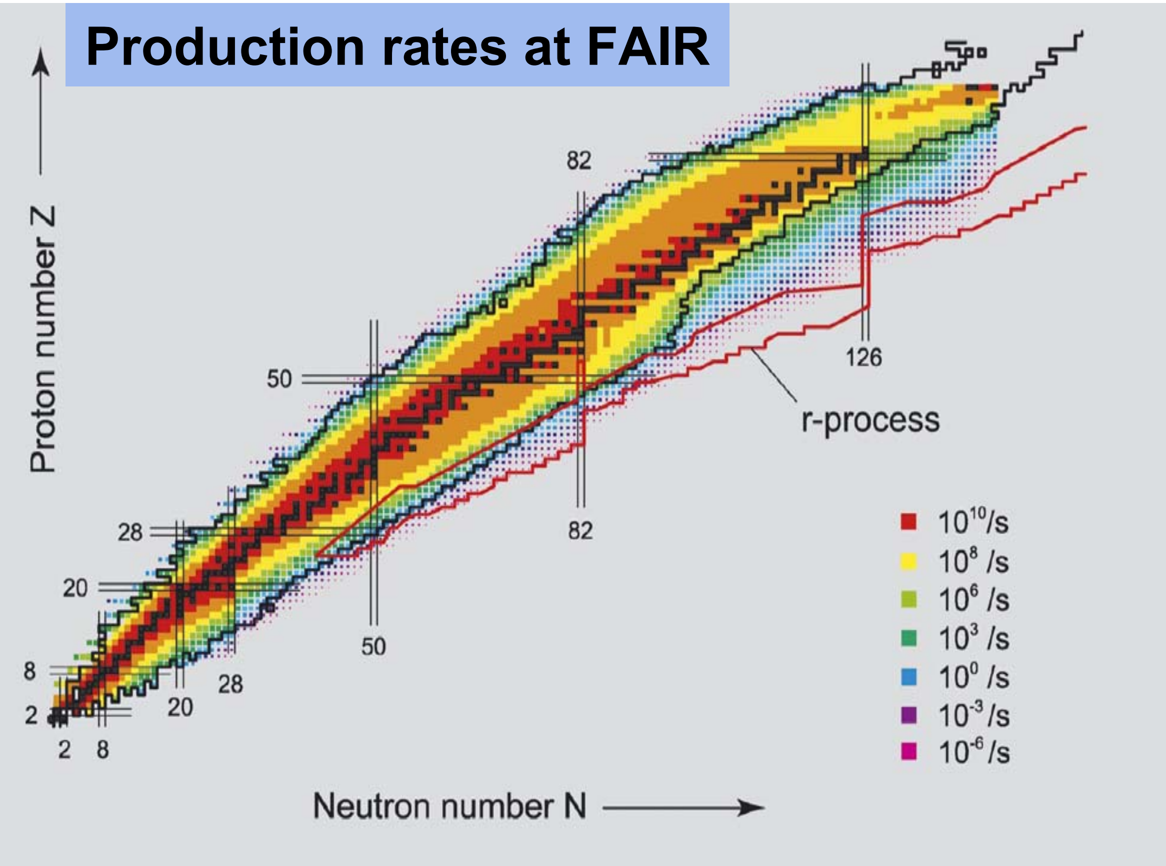
Reactions with Relativistic Radioactive Beams

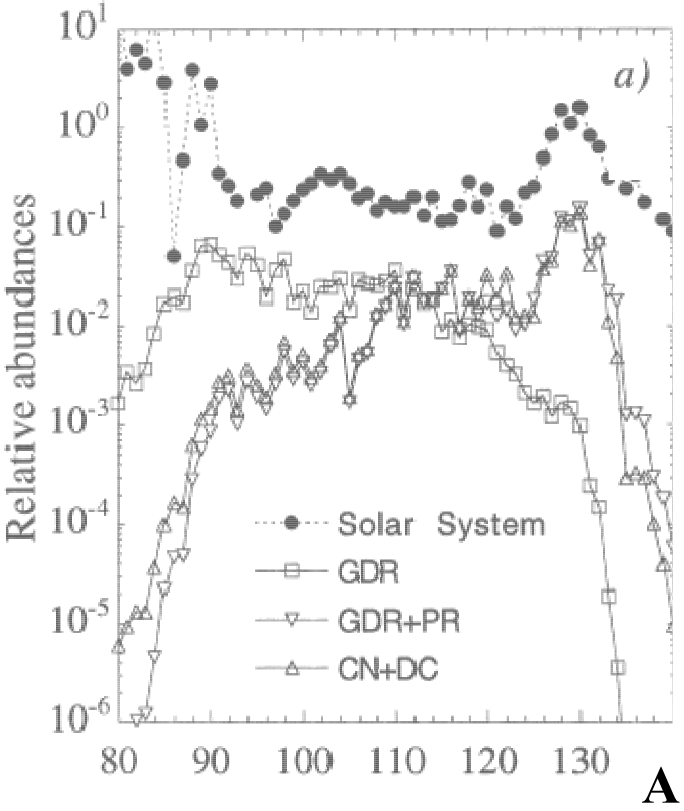


Experiments	Physics goals
➢ elastic scattering	radii, matter distribution
➢ knockout and quasi-free scattering	single-particle occupancies, spectral functions, correlations, clusters, resonances beyond the drip lines
➢ electromagnetic excitation	single-particle occupancies, astrophysical reactions (S factor), soft coherent modes, giant resonance strength, B(E2)
➢ charge-exchange reactions	Gamov-Teller strength, spin-dipole resonance, neutron skins
➢ fission	shell structure, dynamical properties
➢ spallation	reaction mechanism, applications (waste transmutation, ...)
➢ fragmentation	γ-ray spectroscopy, isospin-dependence in multifragmentation

Low-lying dipole strength in the context of r-process nucleosynthesis

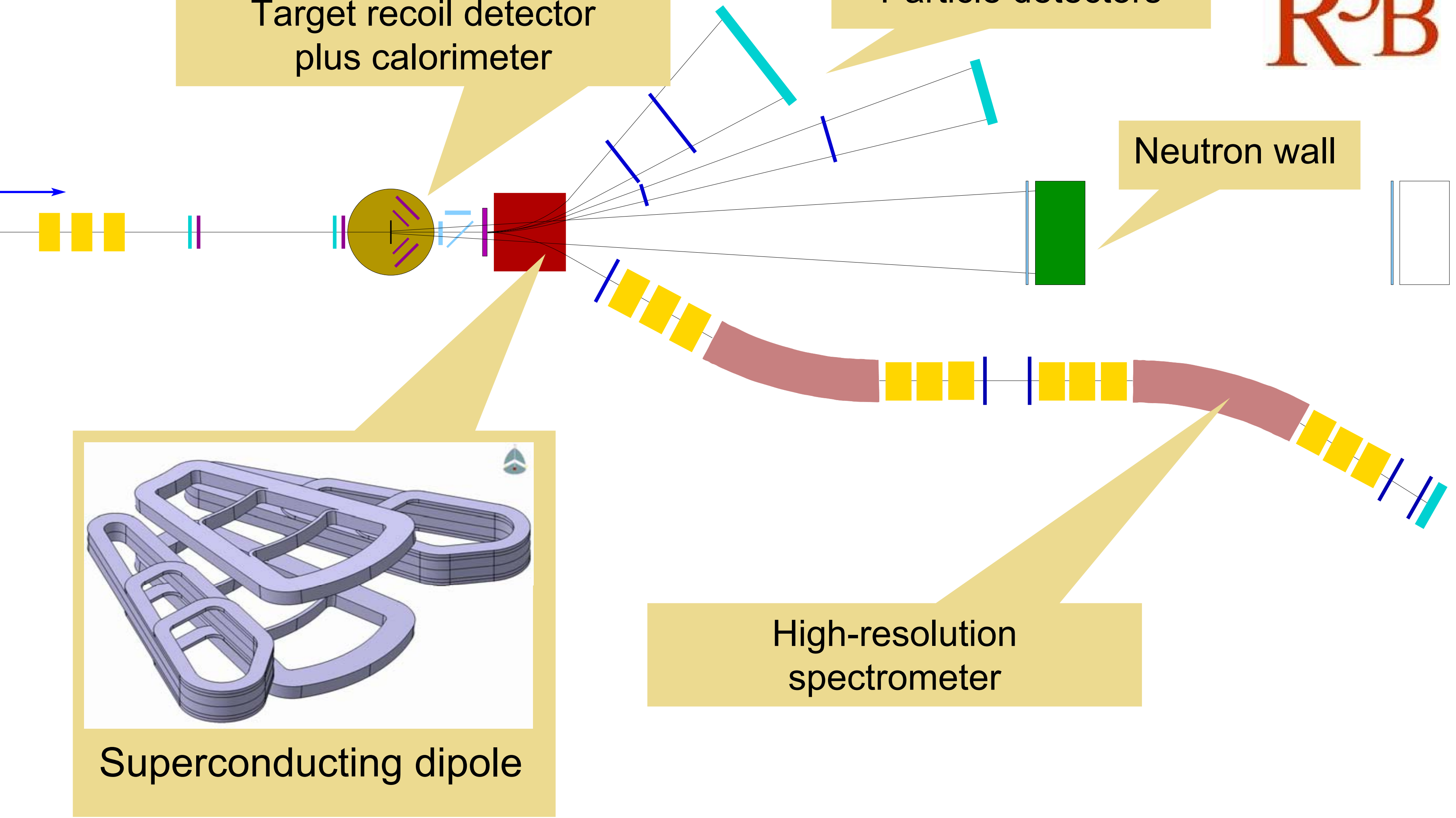
Production rates at FAIR





- S. Goriely, Phys. Lett. B436 (1998) 10-18
- S. Goriely, E. Khan, Nucl. Phys. A706 (2002) 217-232

Reactions with Relativistic Radioactive Beams



Target recoil detector plus calorimeter

Particle detectors

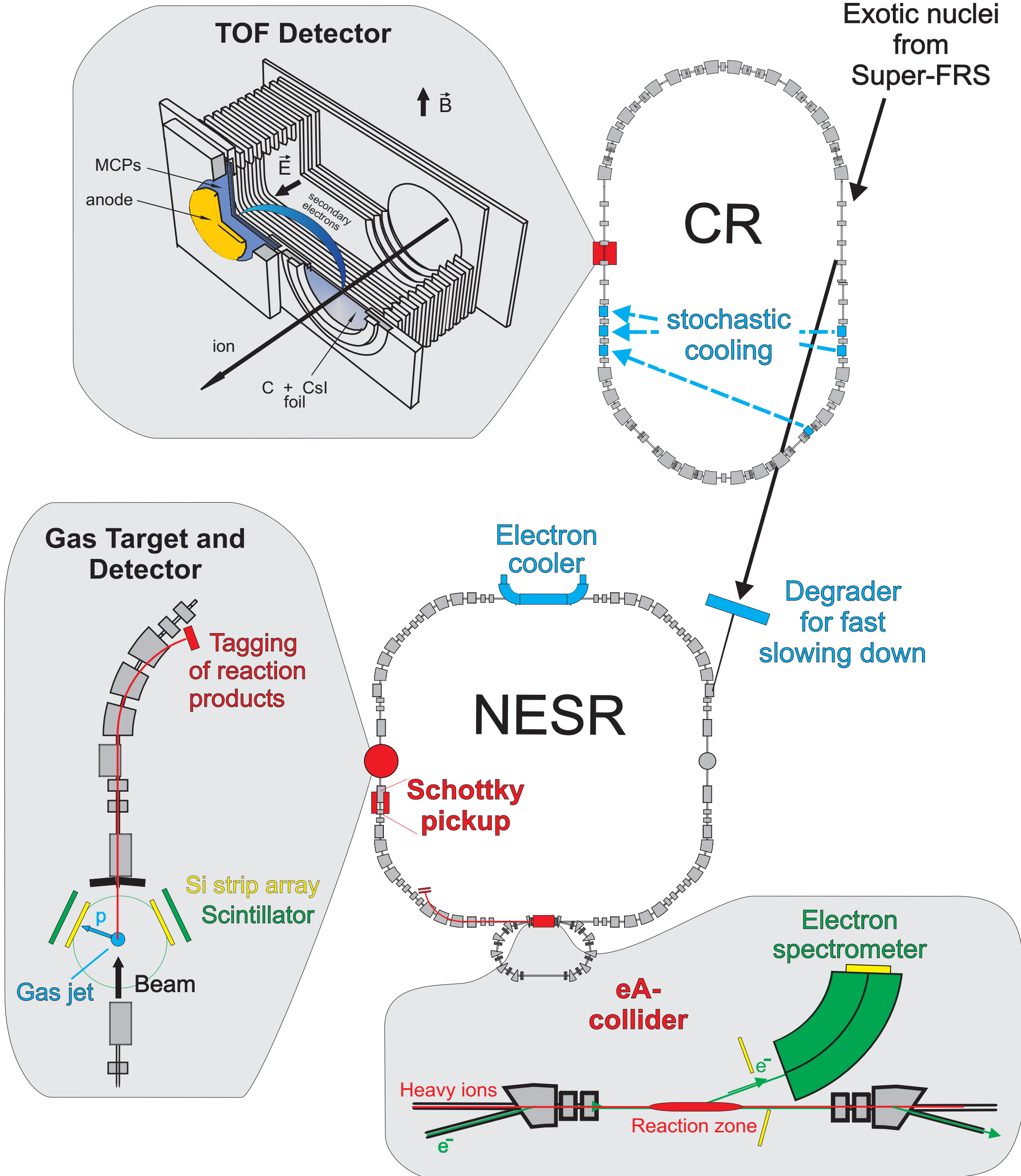
Neutron wall

Superconducting dipole

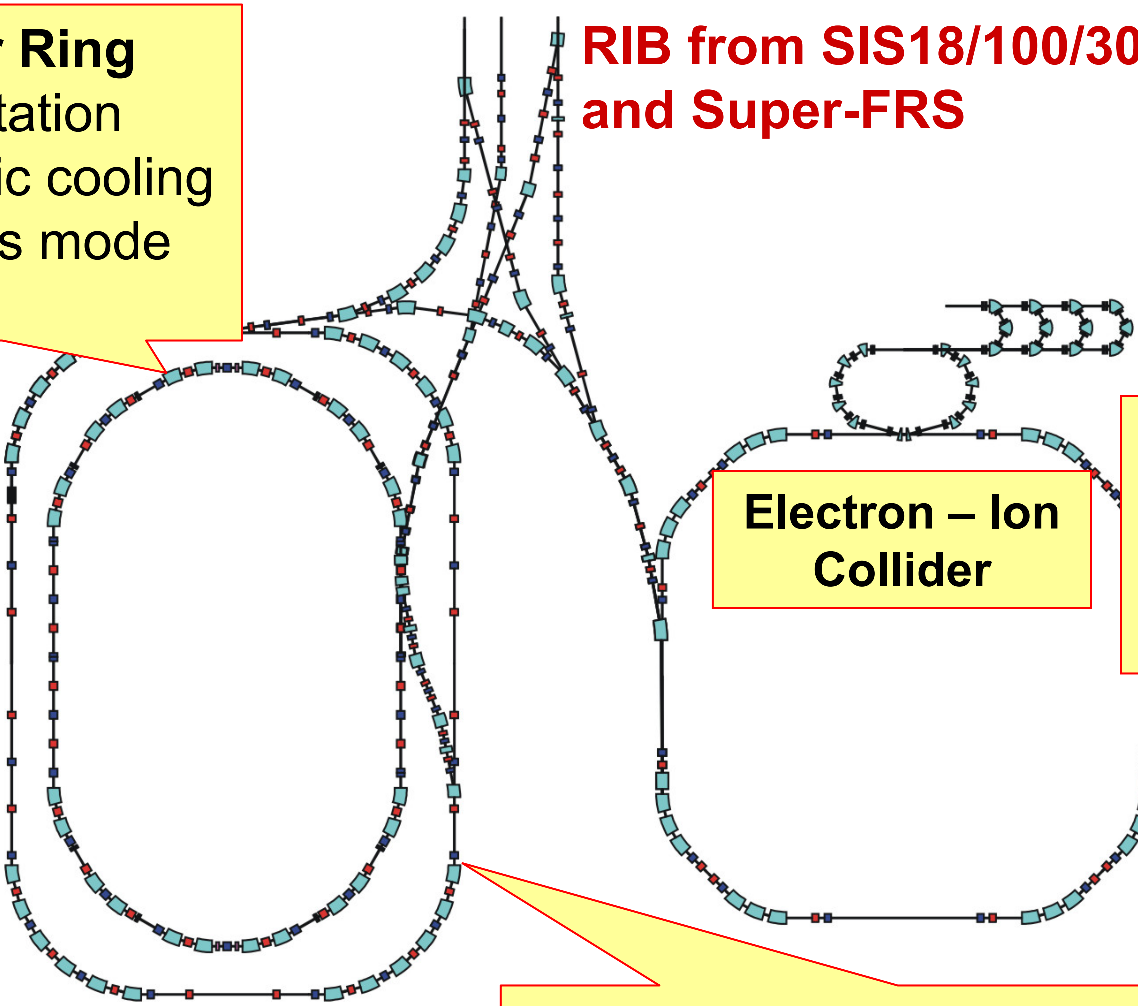
High-resolution spectrometer

Experiments at storage rings

- Mass measurements
- Reactions with internal targets
  - Elastic p scatt.
  - (p,p') (α,α')
  - charge-exchange
  - transfer
- Electron scattering
  - elastic scattering
  - inelastic
- Antiproton-A collider



Storage Rings at FAIR



Collector Ring
bunch rotation
fast stochastic cooling
isochronous mode

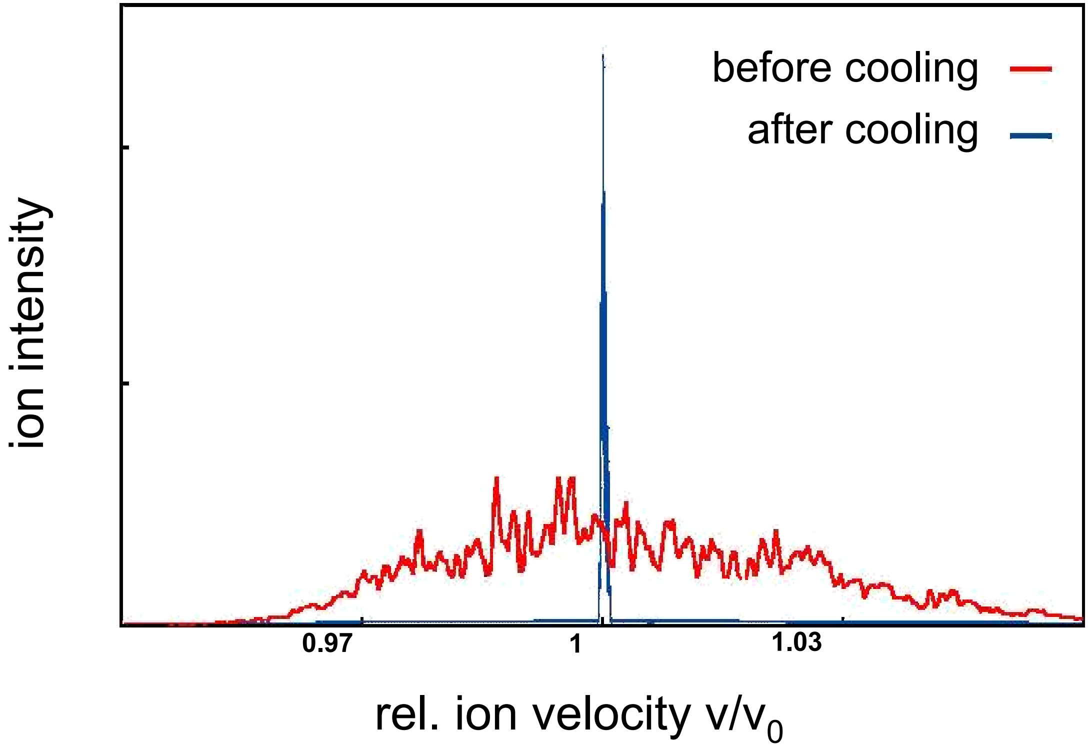
RIB from SIS18/100/300 and Super-FRS

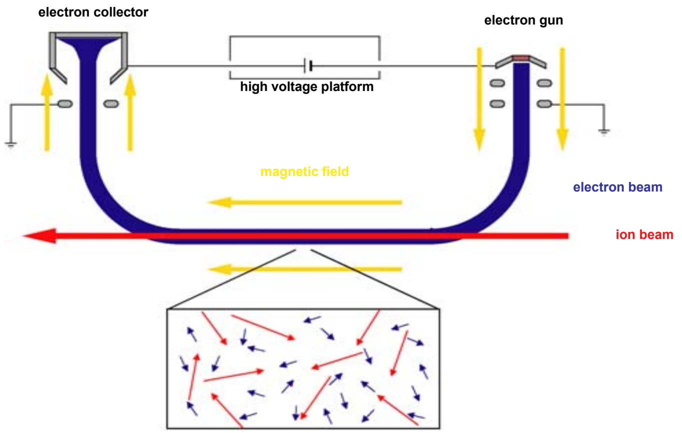
Electron – Ion Collider

NESR
electron cooling
experiments **with** internal target

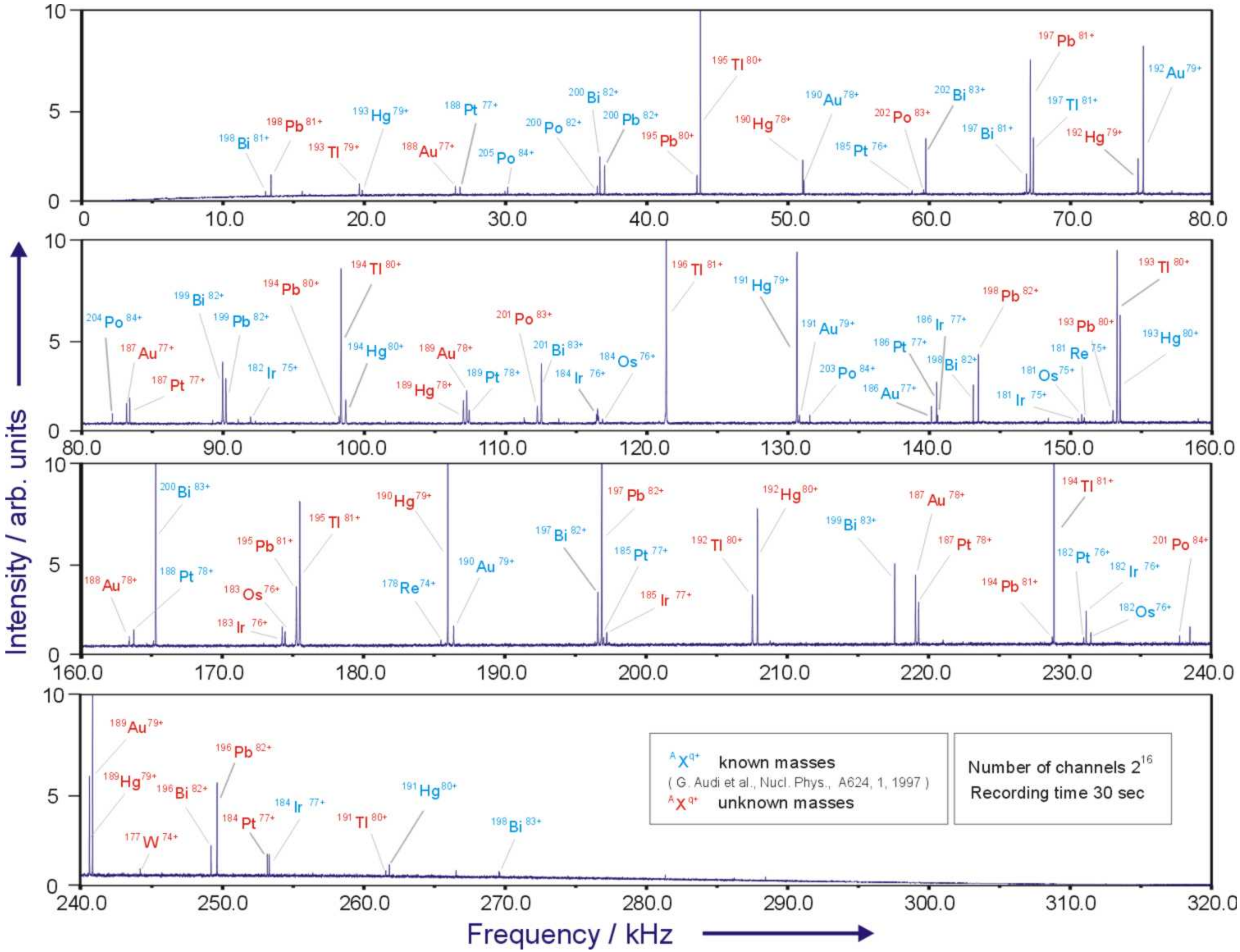
RESR
deceleration (1T/s) to 100 - 400 MeV/u

Storage rings: Cooled beams

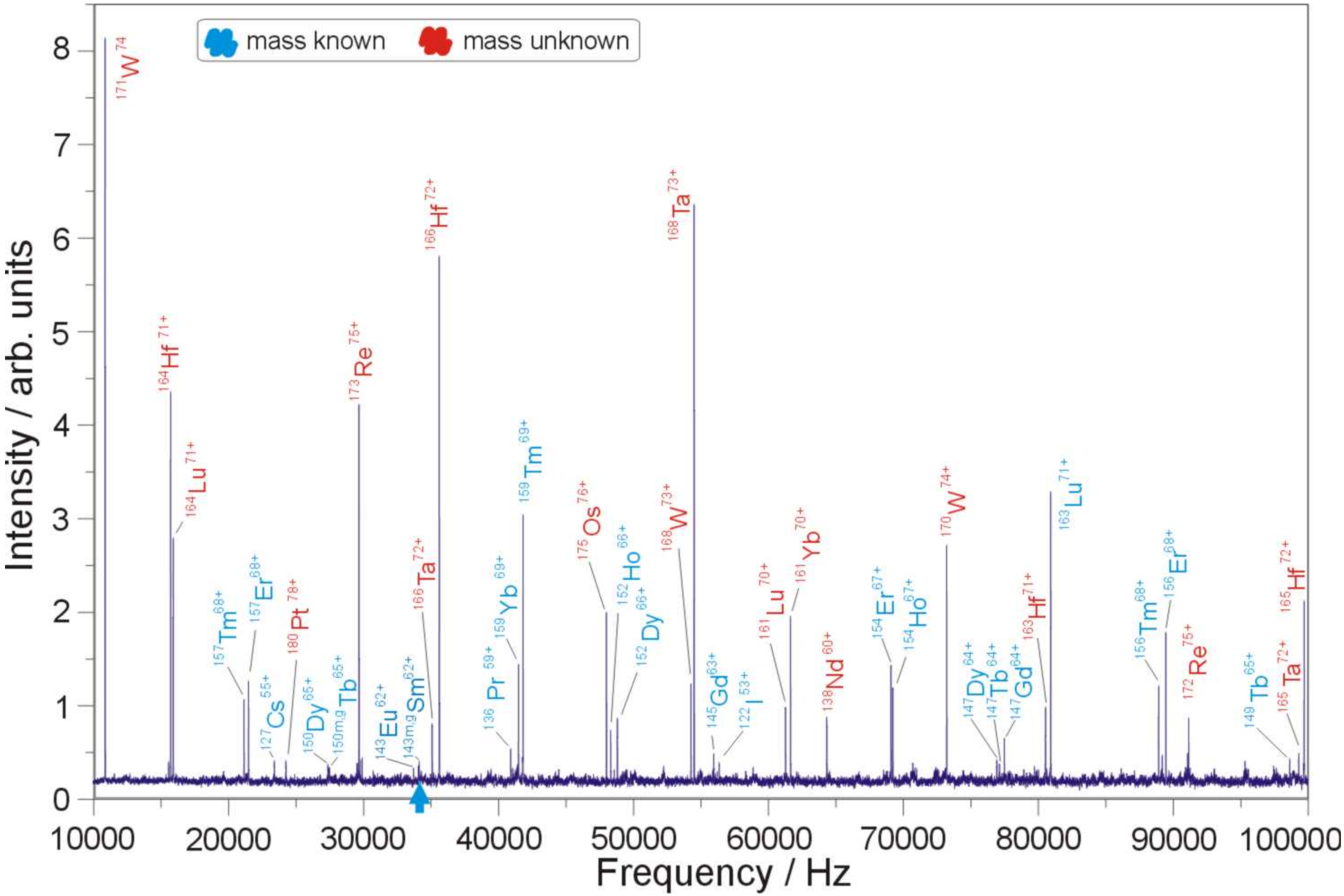




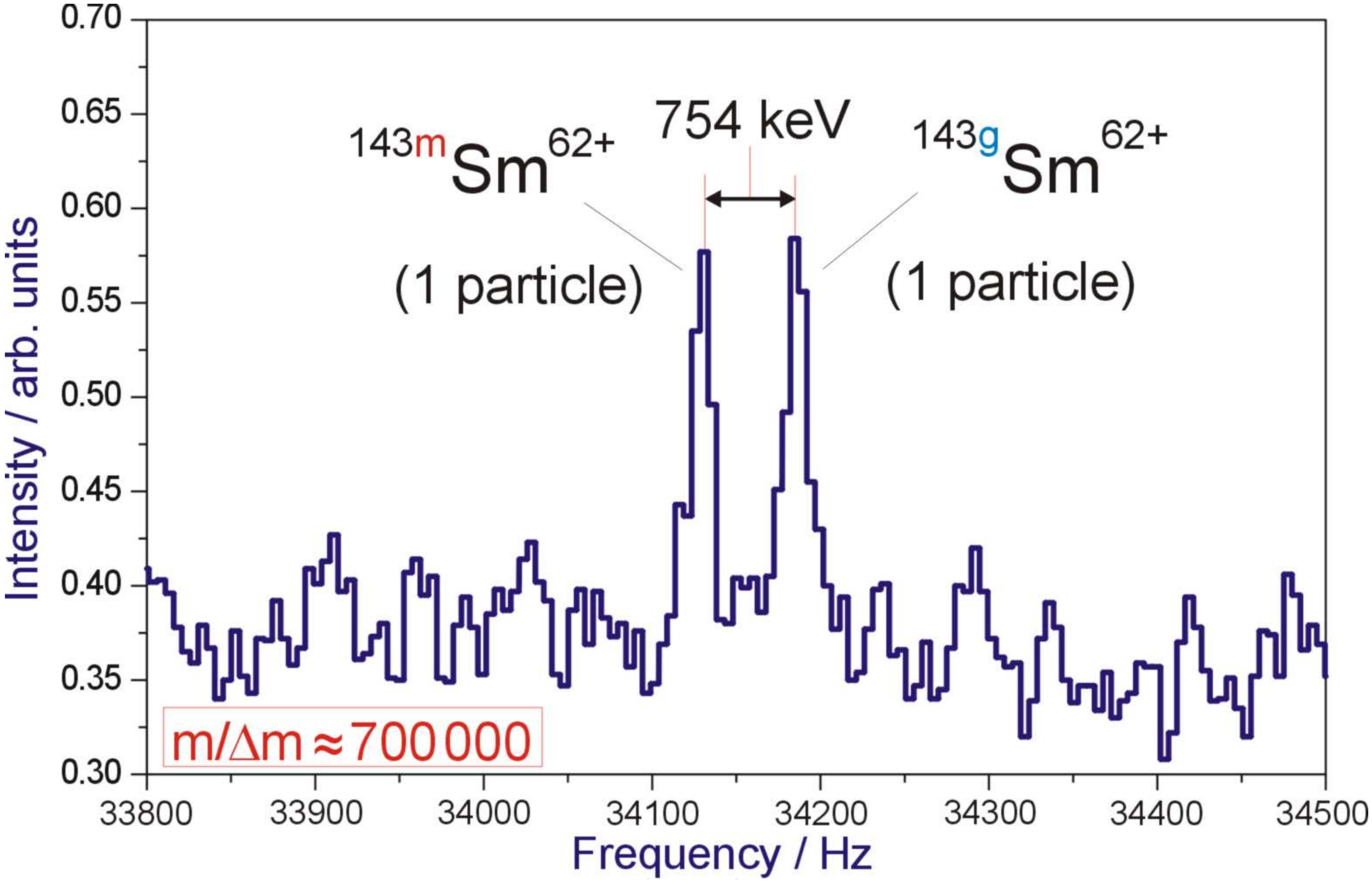
Schottky frequency spectra



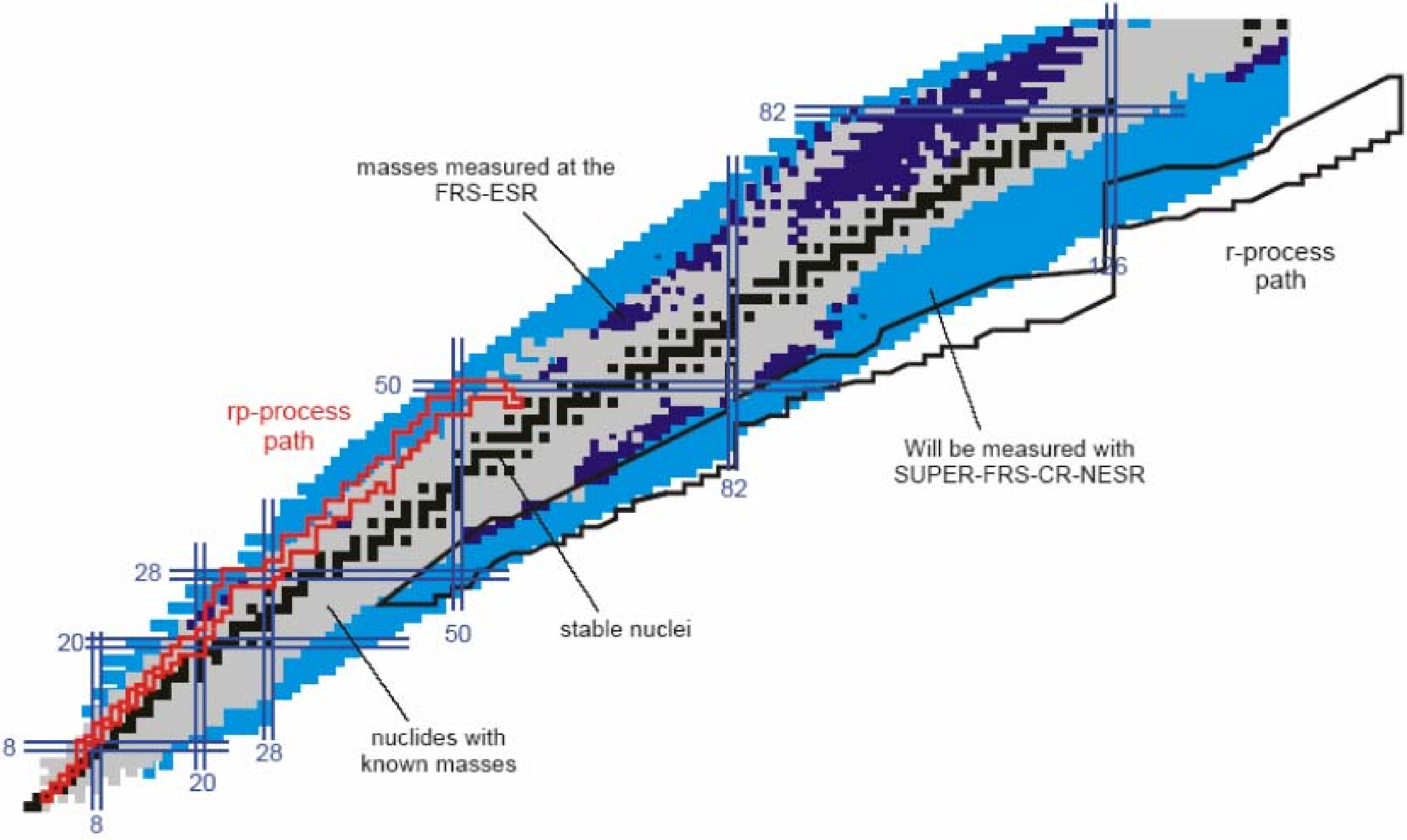
Schottky frequency spectra



Schottky frequency spectra



Mass measurements at NuSTAR/FAIR (ILIMA)



The collective response of the nucleus: Giant Resonances

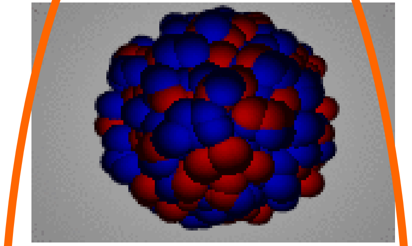
Electric giant resonances

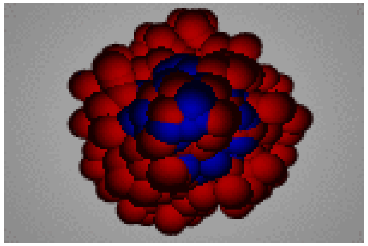
Isoscalar

Isovector

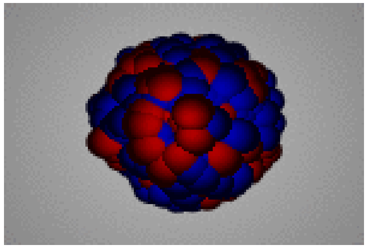
Photo-neutron cross sections

Monopole (GMR)

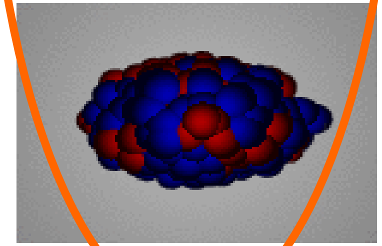


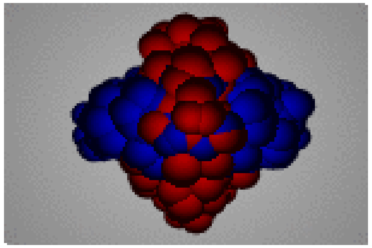


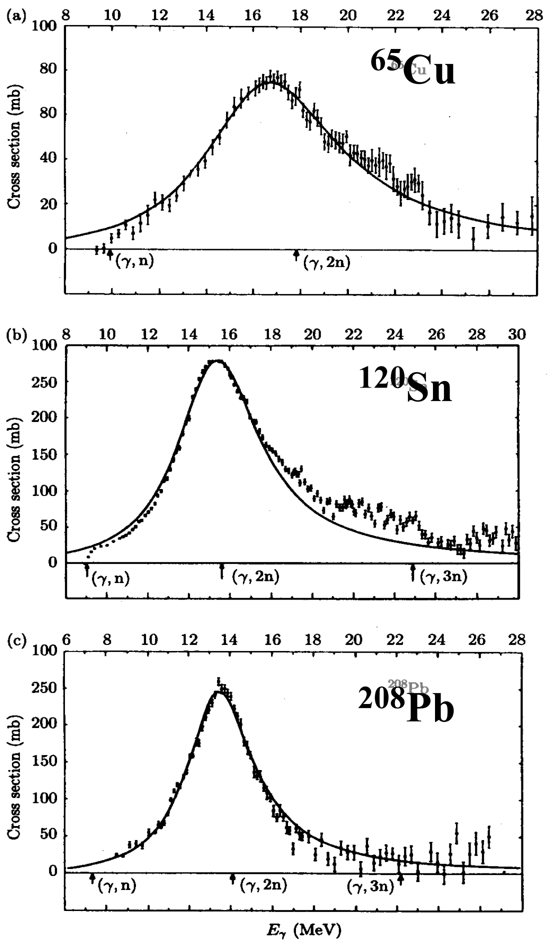
Dipole (GDR)



Quadrupole (GQR)







Berman and Fulz, Rev. Mod. Phys. 47 (1975) 47

Light-ion scattering in the storage ring (EXL)

Scattering in inverse kinematics

Low-momentum transfer region often most important, e.g.,

- giant monopole excitation
- elastic scattering

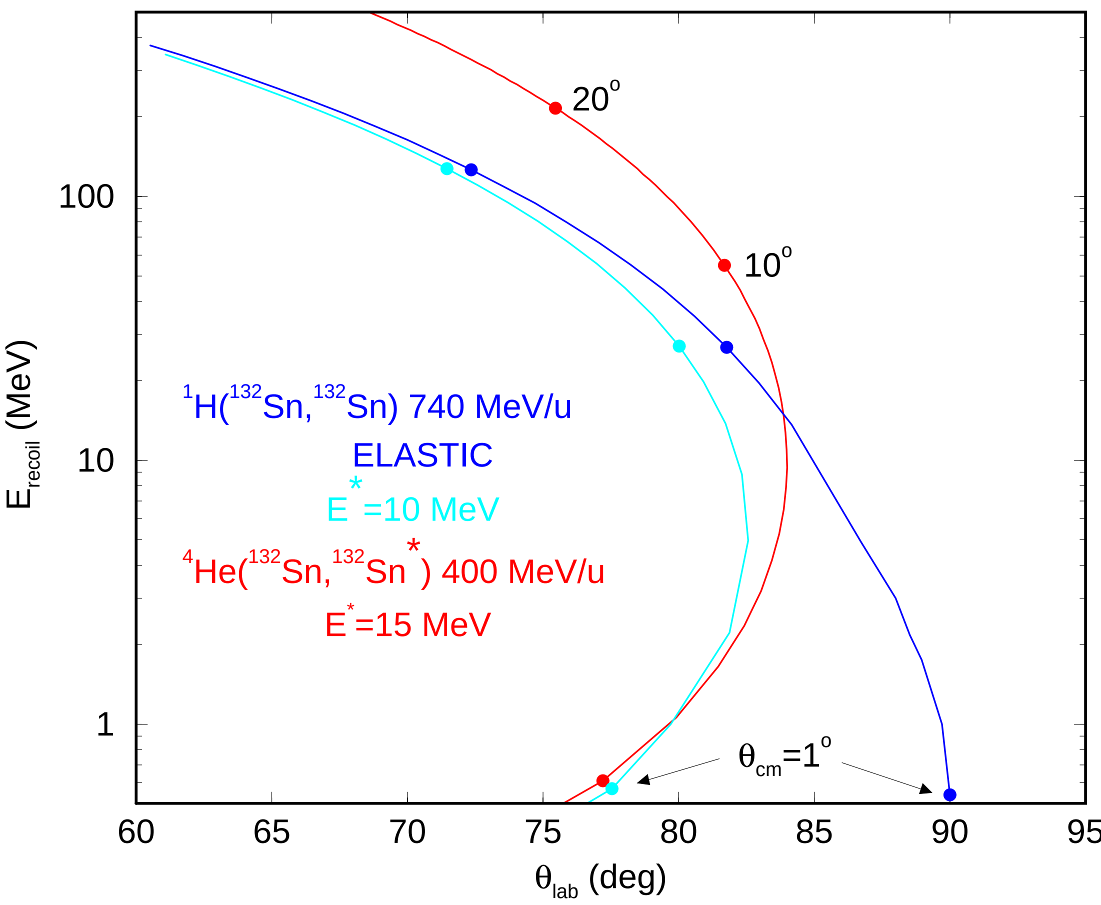
Experimental difficulty

- low recoil energies
- thin targets (low luminosity)

EXL solution:

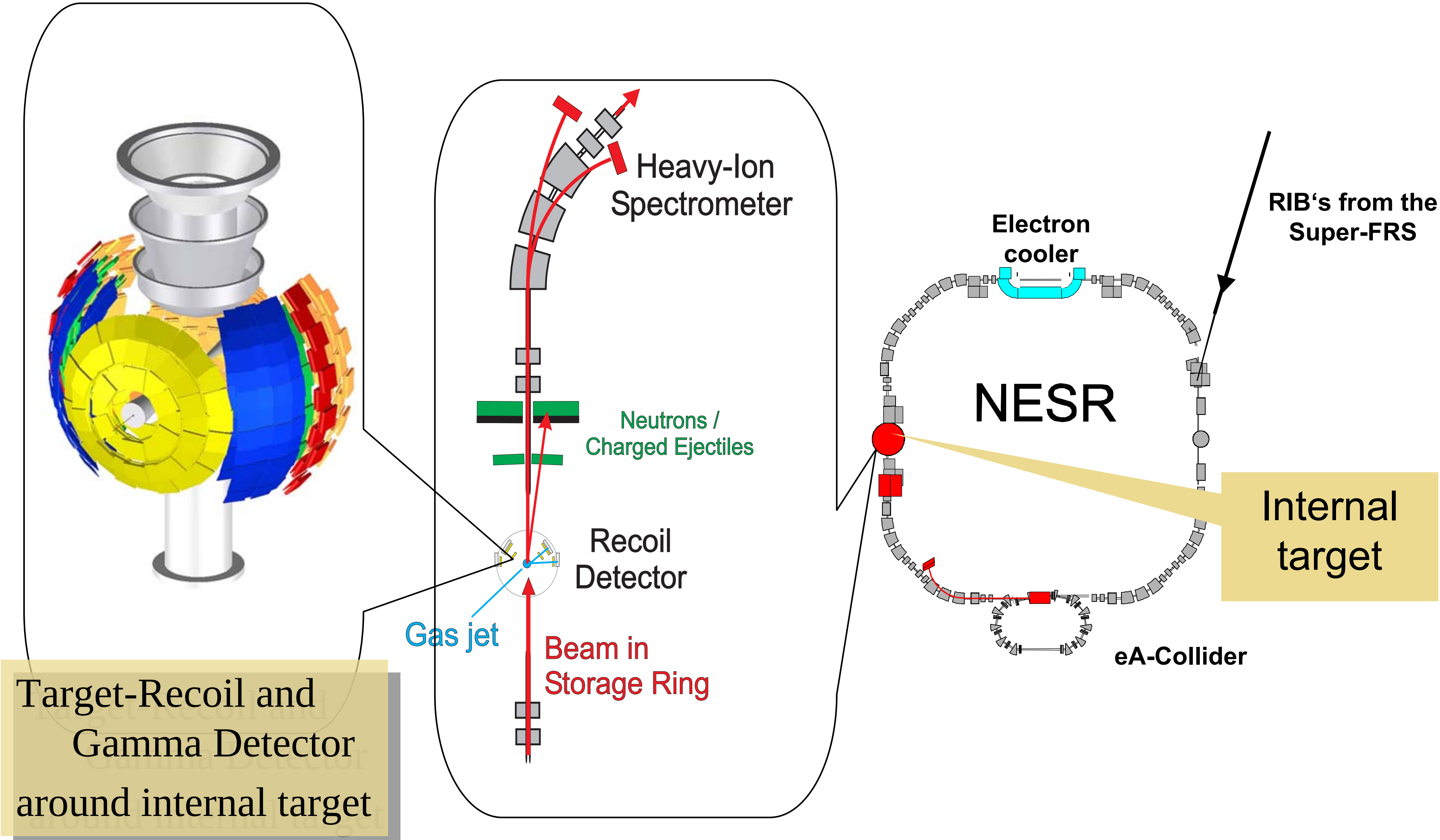
in-ring scattering at internal gas-jet targets

gaining back luminosity due to circulation frequency of ~ 10^6



The EXL experiment

EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring



Heavy-Ion Spectrometer

Neutrons / Charged Ejectiles

Recoil Detector

Gas jet

Beam in Storage Ring

Electron cooler

RIB's from the Super-FRS

NESR

Internal target

eA-Collider

Target-Recoil and
Gamma Detector
around internal target

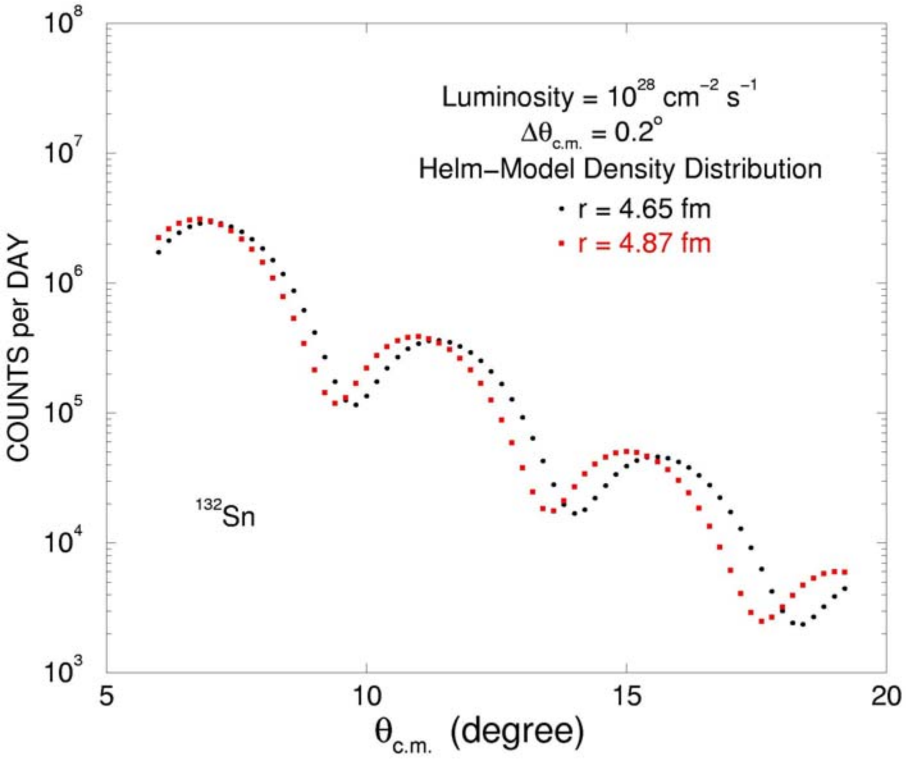
Scattering at internal targets

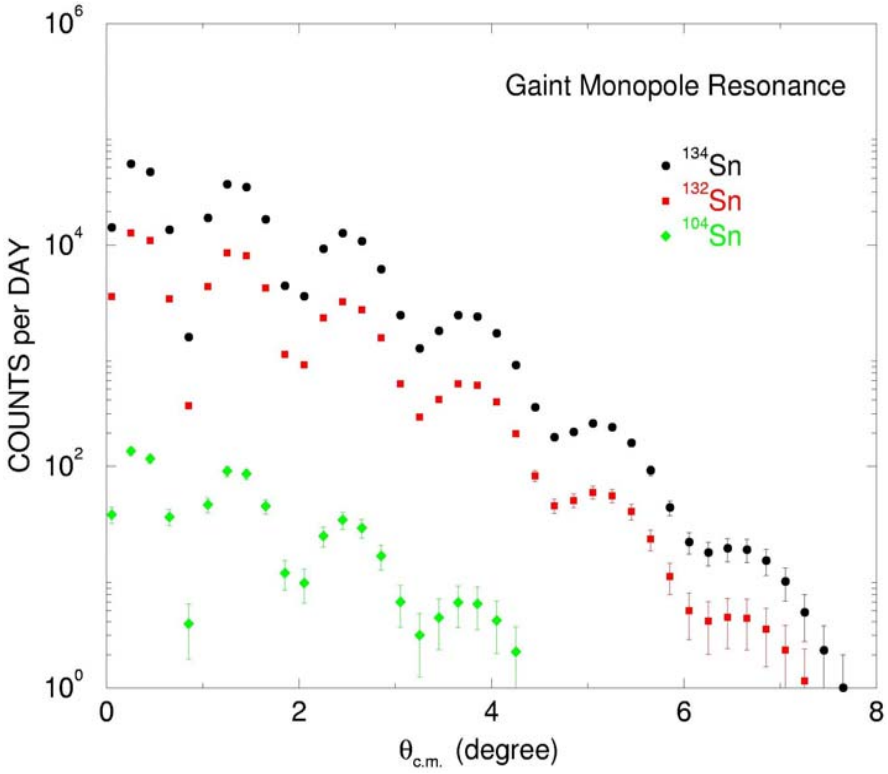
Elastic proton scattering ^{132}Sn

-> matter distribution

Inelastic alpha scattering on Sn isotopes

(Giant Monopole resonance)

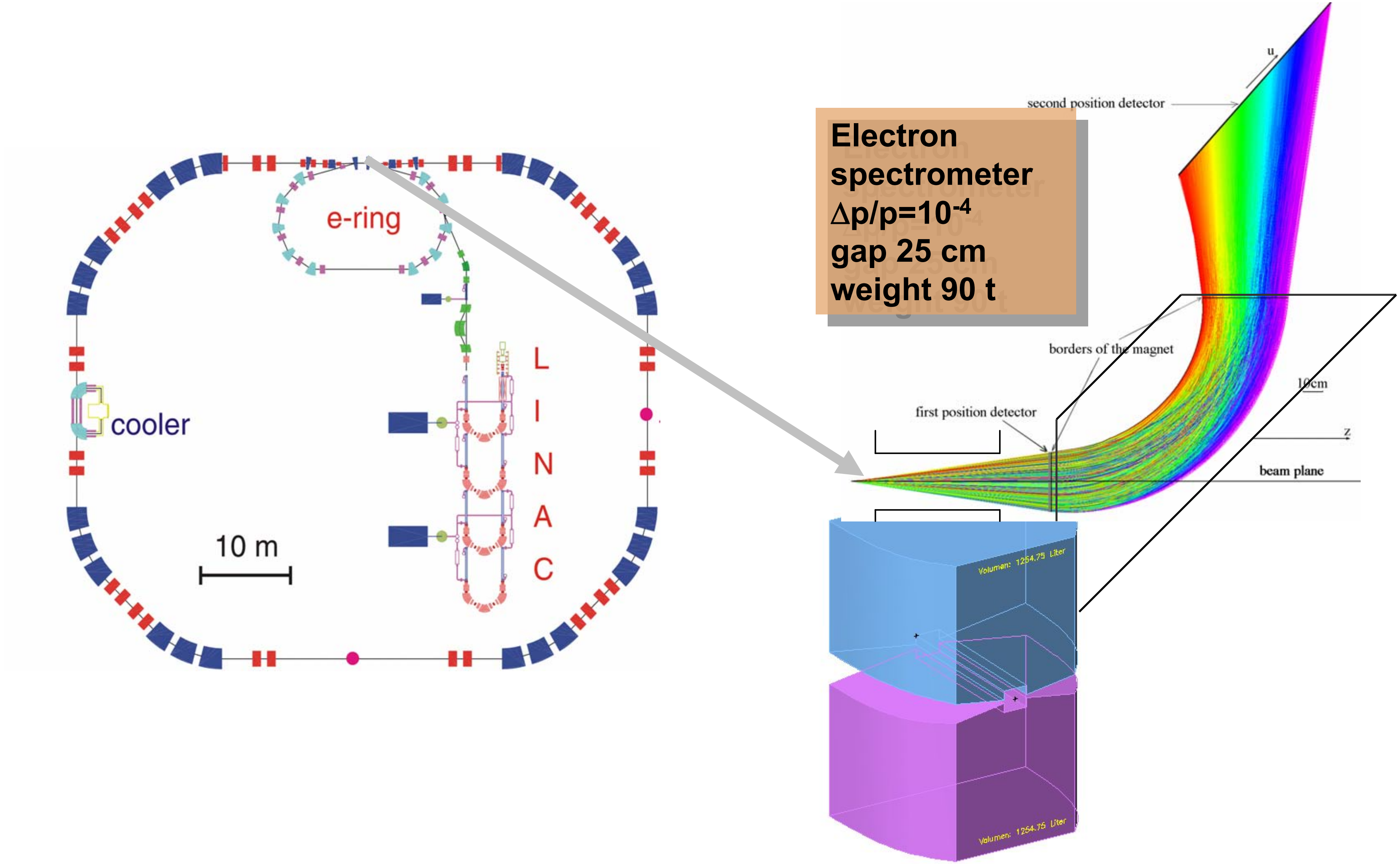




Light-ion / electron scattering

density distributions	elastic scattering (p,p) , (α,α) (e,e)	radii, skin, halo
shell structure in-medium interactions N-N correlations	quasi-free scattering (p,2p), (p,np) (e,e'p)	shell occupancy spectral $S(\omega,q)$
collective modes	inelastic scattering (p,p'), (α, α') (e.e')	mixed isoscalar-isovector modes
spin-isospin excitations	charge exchange (p,n), (d,^{2}He), (^{3}He,t) (e,e')	weak transition rates GT (astrophysics) M1
cluster correlations	quasi-free scattering (p, p α) , (p,p2n) (e, e'α)	cluster knockout

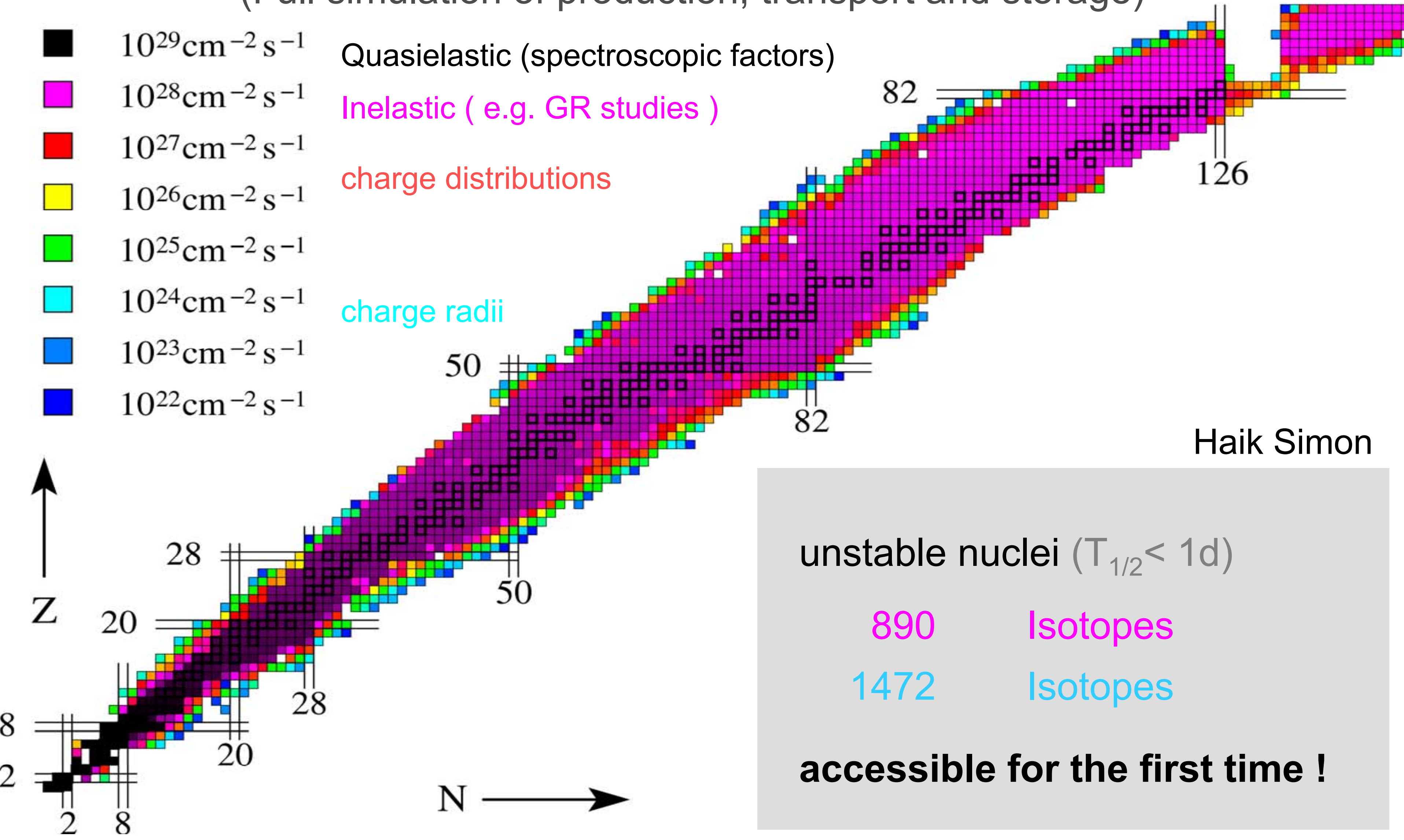
ELISe
The Electron-Ion (eA) Collider



Electron spectrometer
$\Delta p/p=10^{-4}$
gap 25 cm
weight 90 t

Luminosities

(Full simulation of production, transport and storage)



Quasielastic (spectroscopic factors)

Inelastic (e.g. GR studies)

charge distributions

charge radii

Haik Simon

unstable nuclei ($T_{1/2}$< 1d)

890 Isotopes

1472 Isotopes

accessible for the first time !

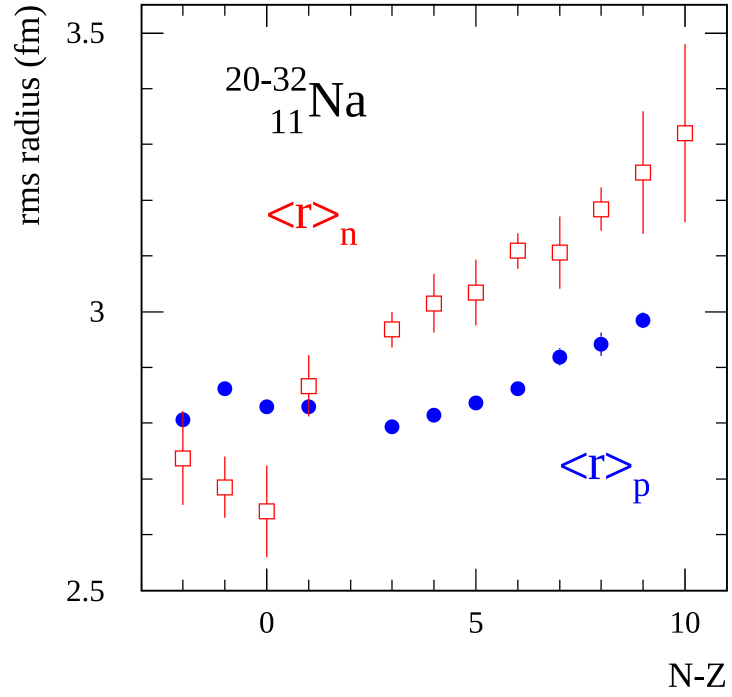
Electron and Proton scattering

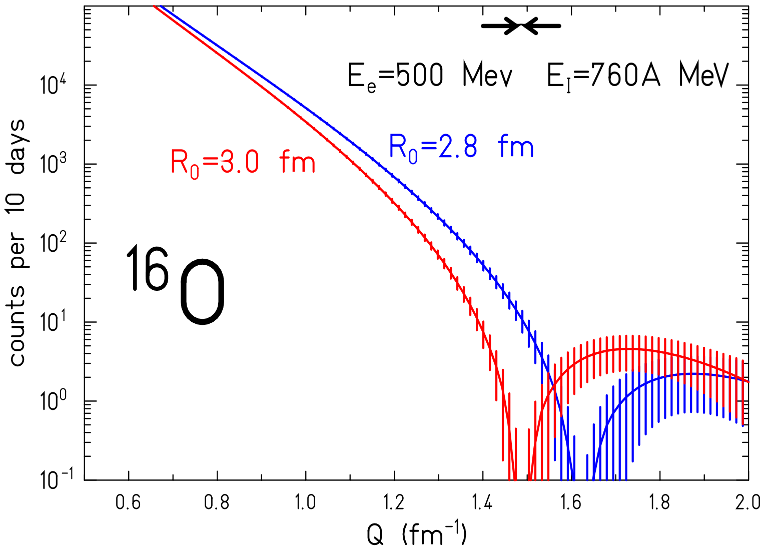
Elastic proton scattering:
Matter distribution

Elastic electron scattering:
Charge distribution

Both combined:
Halos, skins, diffuseness

→ Symmetry energy, Equation of State, spin-orbit term

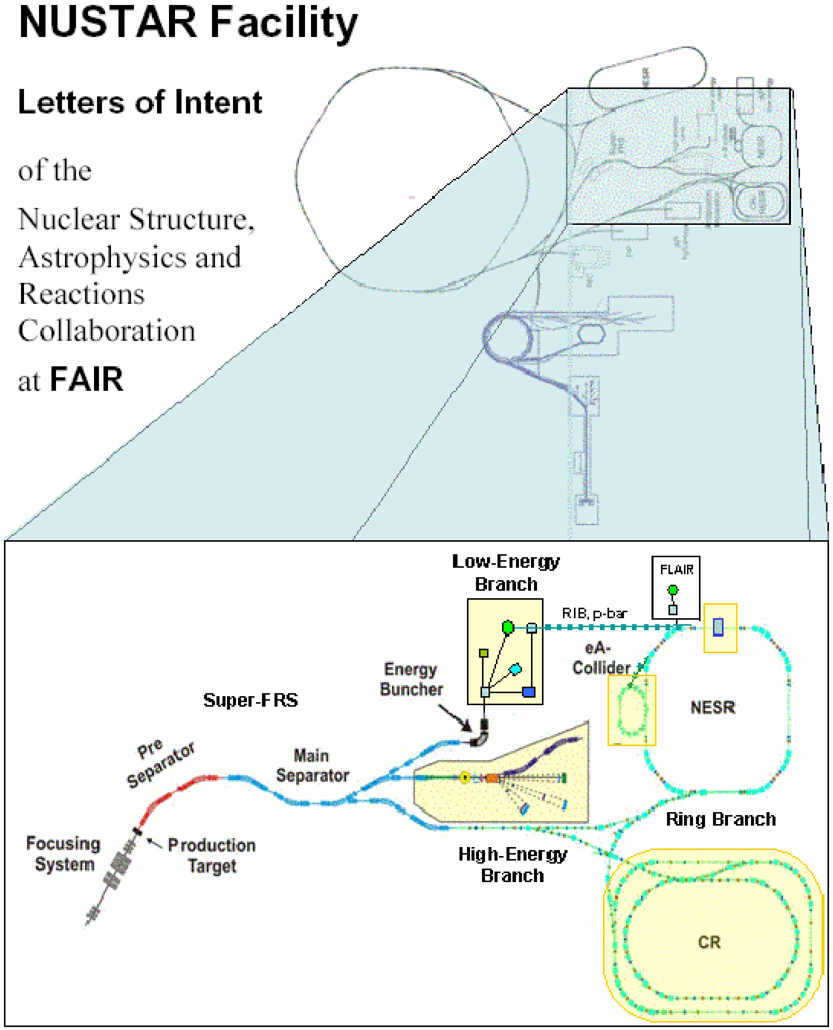




Typical luminosity: 10^{28} cm^{-2} s^{-1}

→ possible for a wide range of nuclei

NuSTAR Letters of Intent



NUSTAR Facility

Letters of Intent

of the

Nuclear Structure,
Astrophysics and
Reactions
Collaboration

at **FAIR**

NuSTAR collaboration

(~700 scientists)

Content

http://www-w2k.gsi.de/superfrs/documents/NUSTAR/LoI/NUSTAR-LOI.pdf

Conclusion

Experimental concepts utilizing reactions with high-energy fragmentation beams to study nuclear structure of radioactive nuclei were developed and optimized successfully in the past 15 years

Radioactive beams:

large emittance

tracking, dispersion matching, cooling, ...

low intensity

efficient setups (kinematical forward focusing, high energy, inverse kinematics, storage ring)

thick targets (high energy)

selective reactions

\+ quantitative reaction models (high beam energy allows approximations) → precise nuclear-structure information

Future: higher intensities, optimized experimental setups

Access to very neutron-(proton-)rich nuclei

New experimental methods

Review: Reactions with fast radioactive beams of neutron-rich nuclei, T. Aumann, EPJ A 26 (2005) 441-478