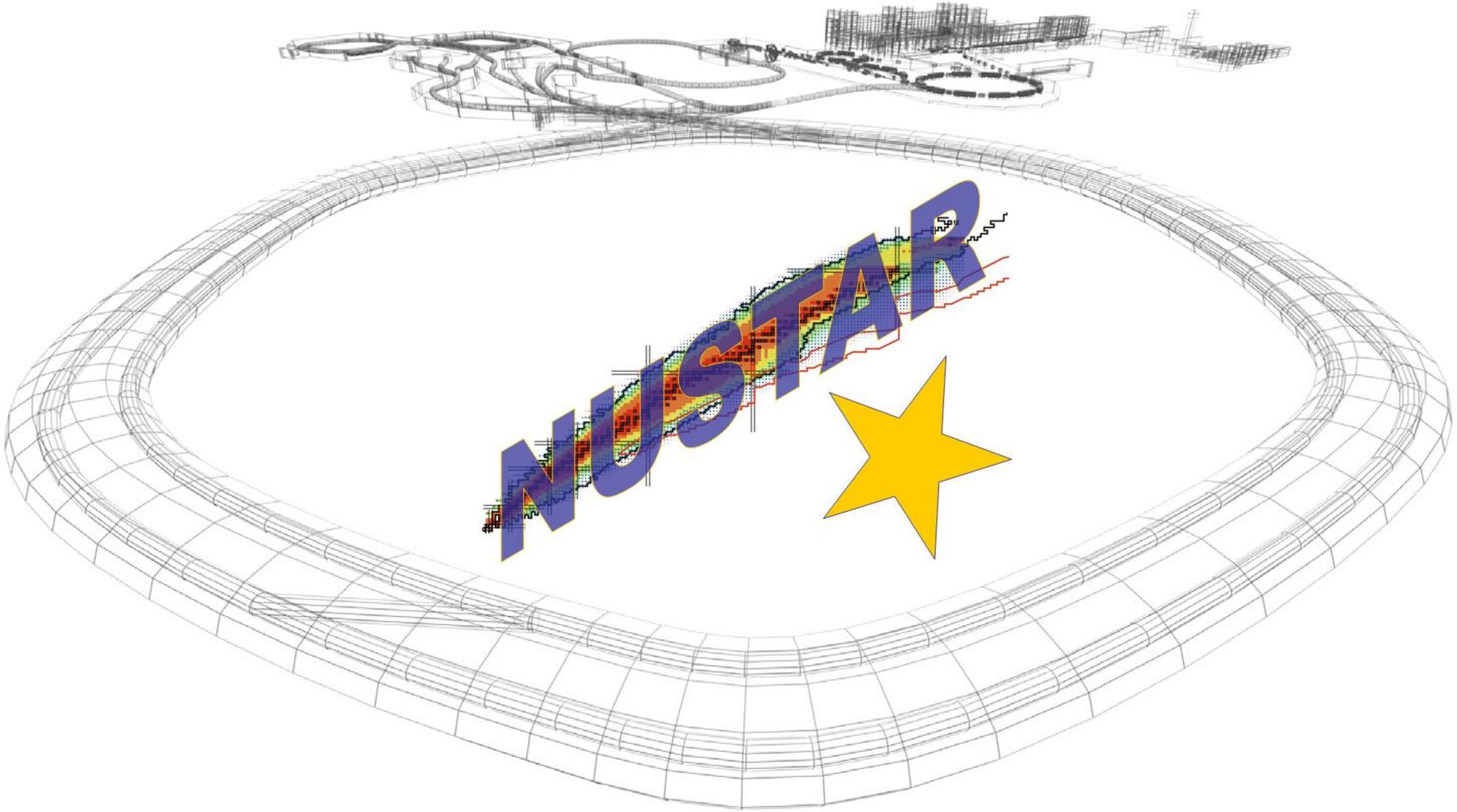
Physics with Exotic Nuclei

Hans-Jürgen Wollersheim



NUclear STructure, Astrophysics and Reaction

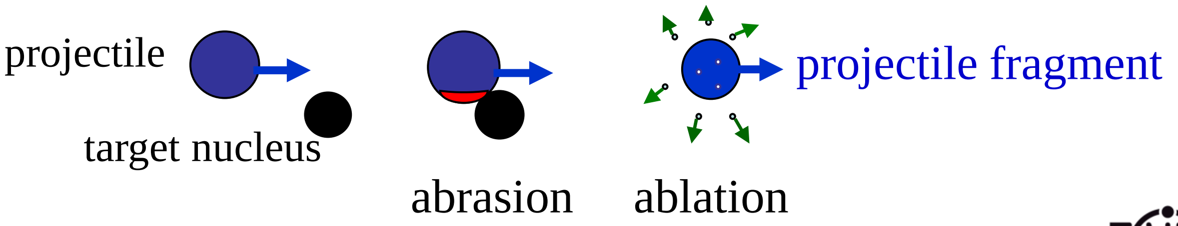
Outline

❖ **Projectile Fragmentation – A Route to Exotic Nuclei**

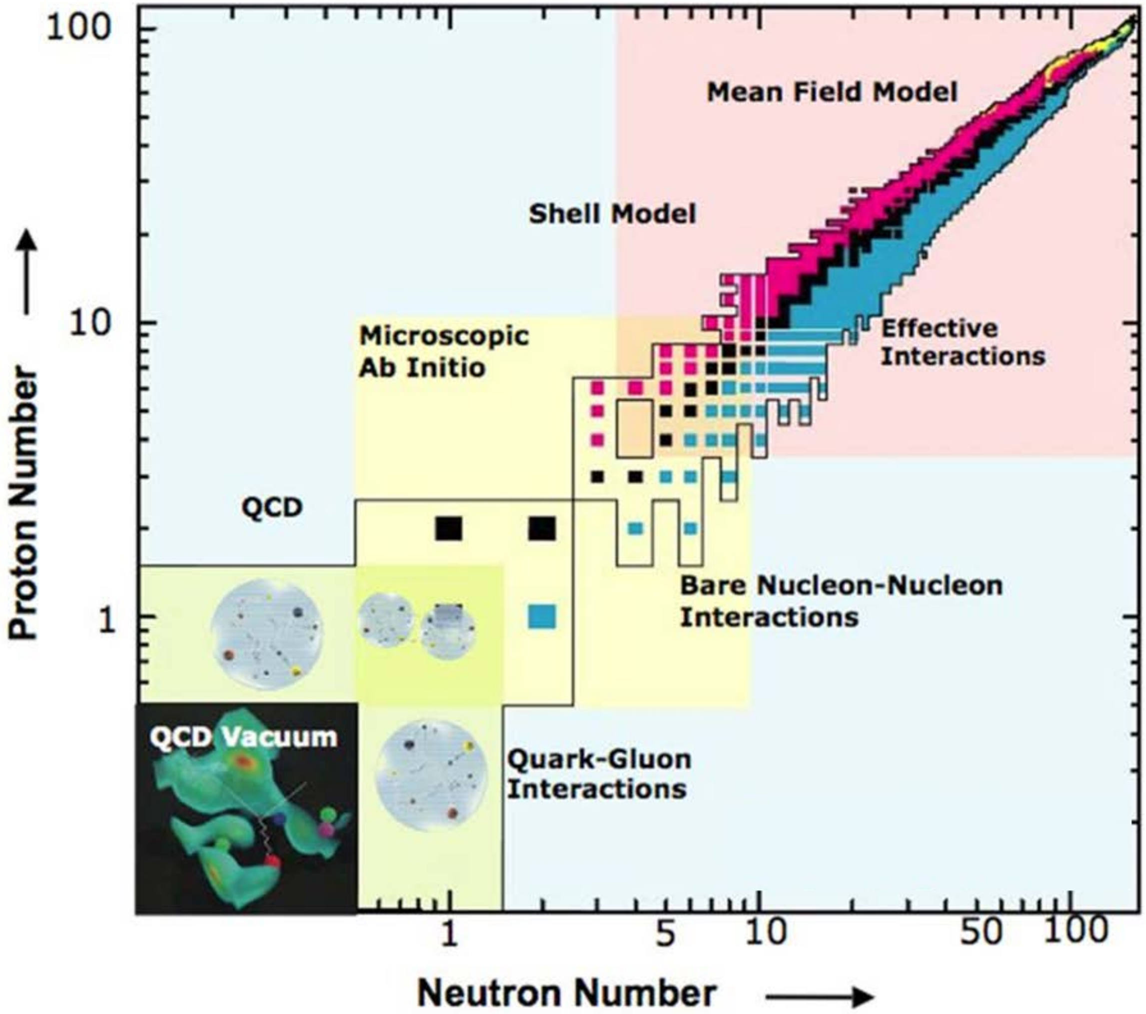
- Fragmentation Cross Sections
- Nuclear Reaction Rates
- In-Flight Separation of **R**adioactive **I**on **B**eams
- **FR**agment **S**eparator at GSI
- Comparison FRS – Super-FRS
- Identification of **RIB**s

❖ Excited Fragments – Gateway to Nuclear Structure

❖ Scattering Experiments with **RIB**s

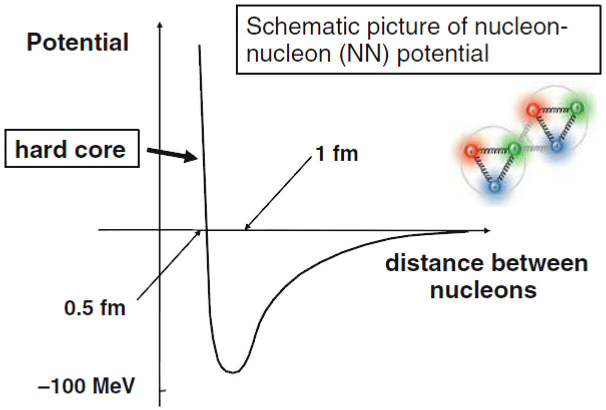


The Why and How of Radioactive-Beam Research

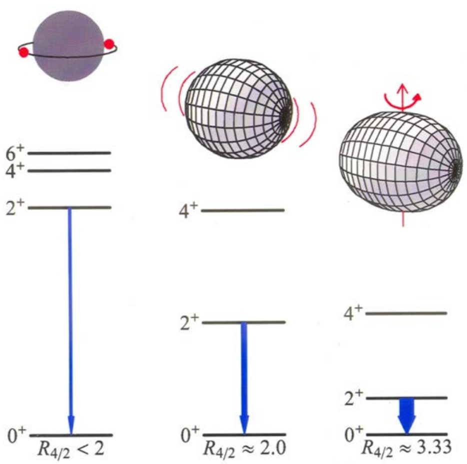


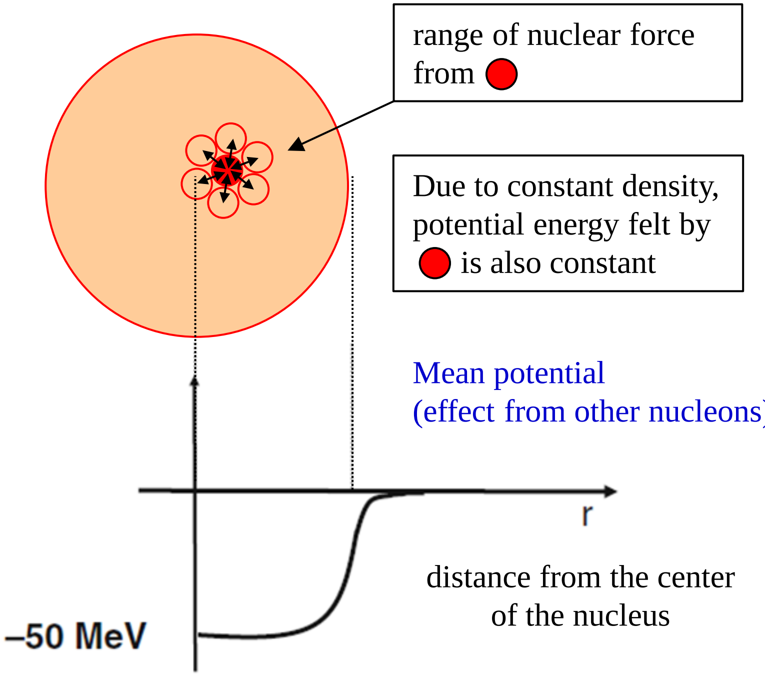
The Why and How of Radioactive-Beam Research

- Atomic nuclei are quantum systems with a finite number of strongly interacting fermions: protons and neutrons.



- Light nuclei up to A=12 are described by bare nucleon-nucleon interaction.
- In heavier nuclei the interactions between the nucleons are modified by the medium → effective interactions are needed.





- How can collective phenomena be explained from individual motion?

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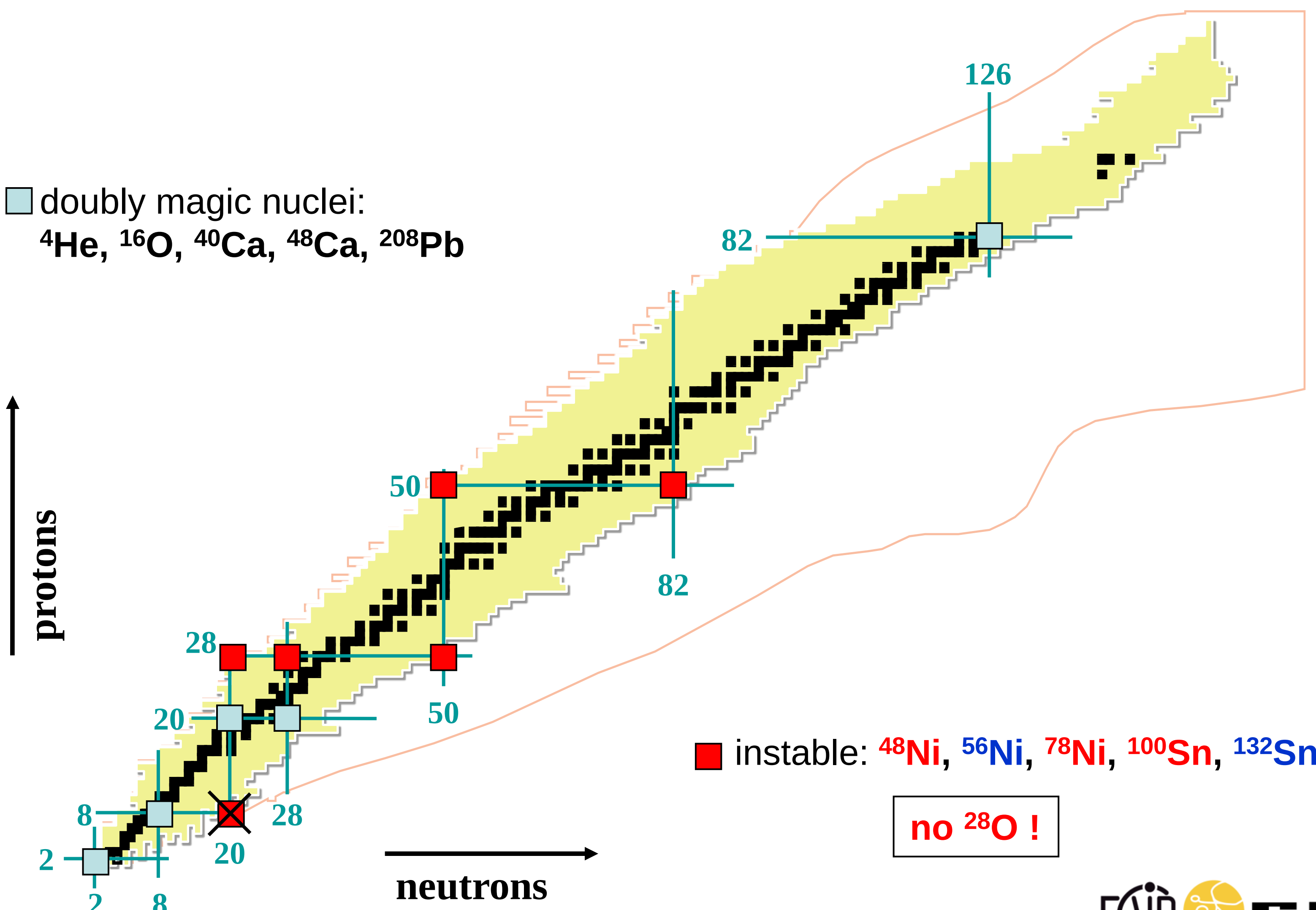
The Nuclear Chart

Our Road Map from Stable to Exotic Nuclei

doubly magic nuclei:
^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca, ^{208}Pb



instable: ^{48}Ni, ^{56}Ni, ^{78}Ni, ^{100}Sn, ^{132}Sn

no ^{28}O !

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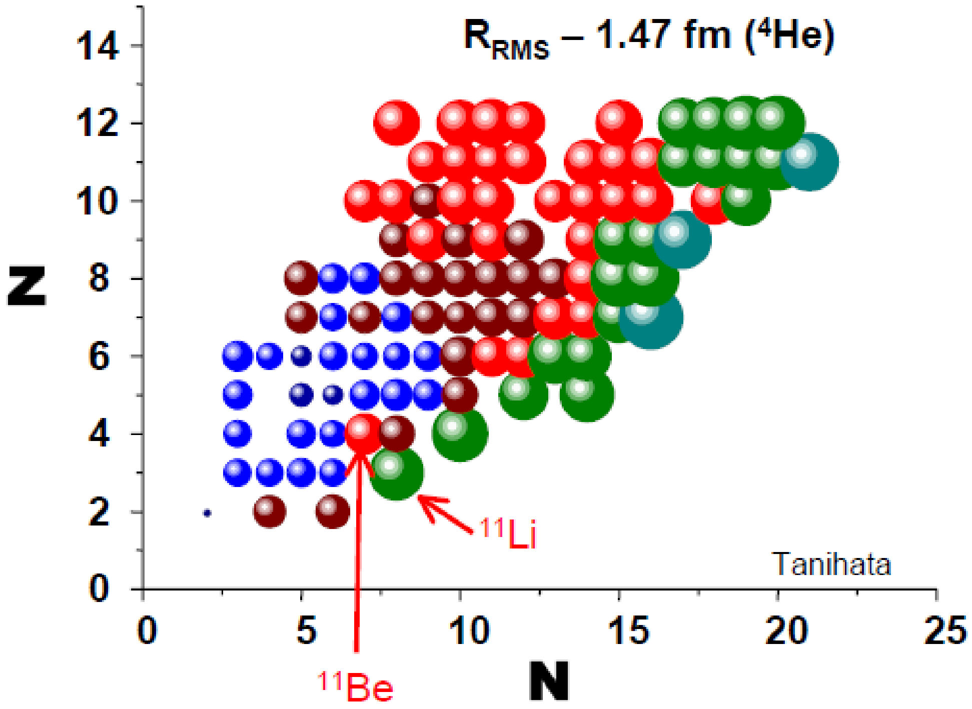
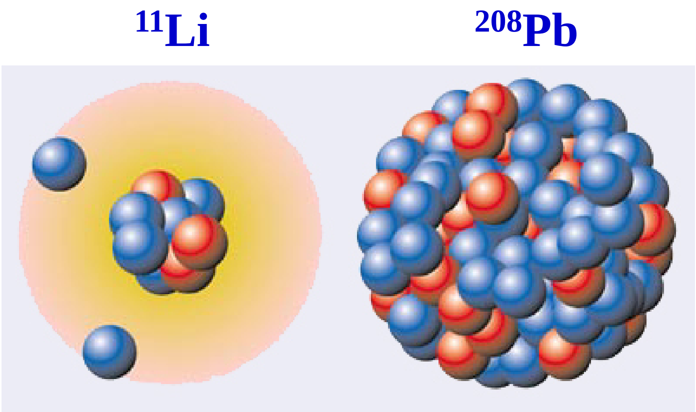
Nuclear radii

❖ textbooks says: $R=1.2\cdot A^{1/3}$

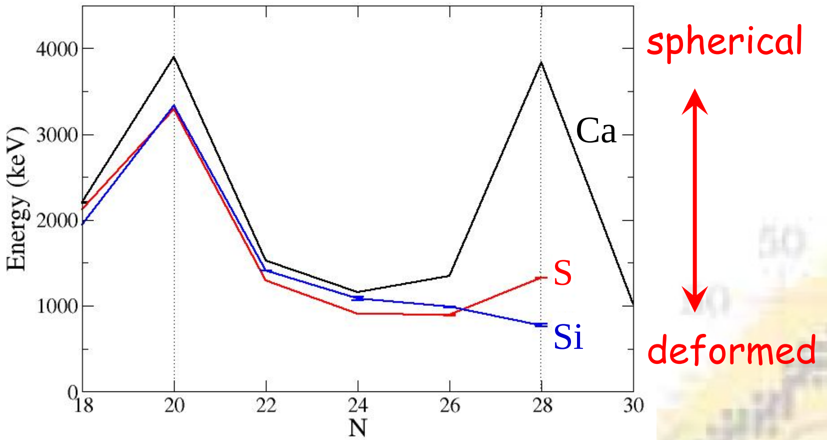


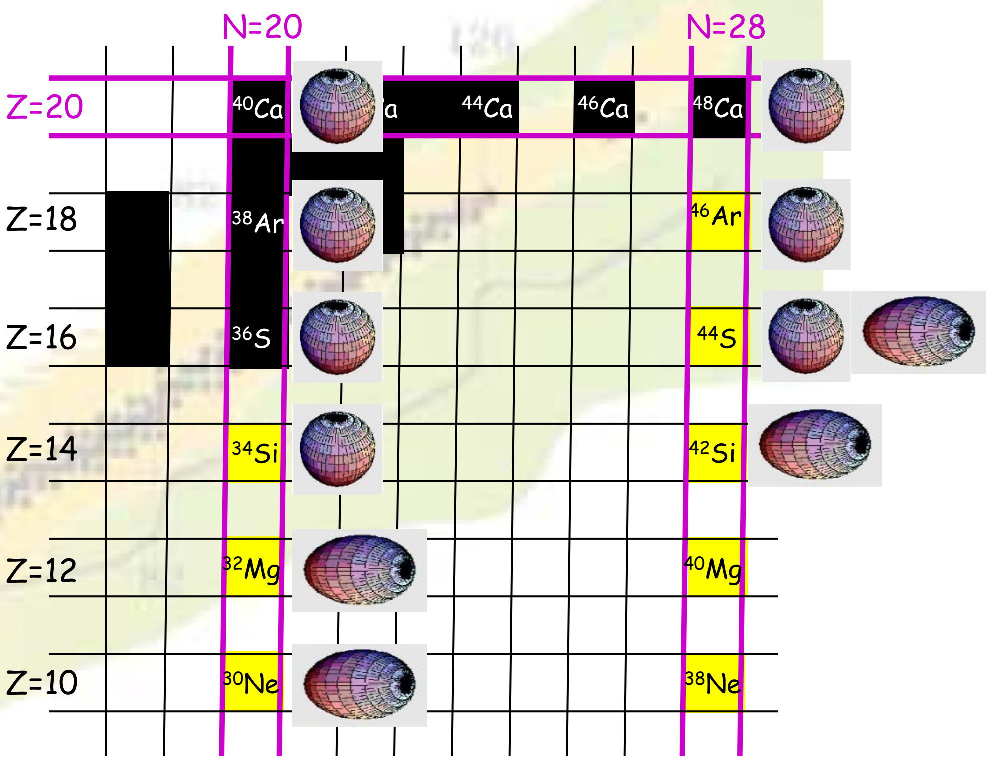


Prog. Part. Nucl. Phys. 59 (2007), 432

Nuclear shell structure

Experimental evidence of magic numbers





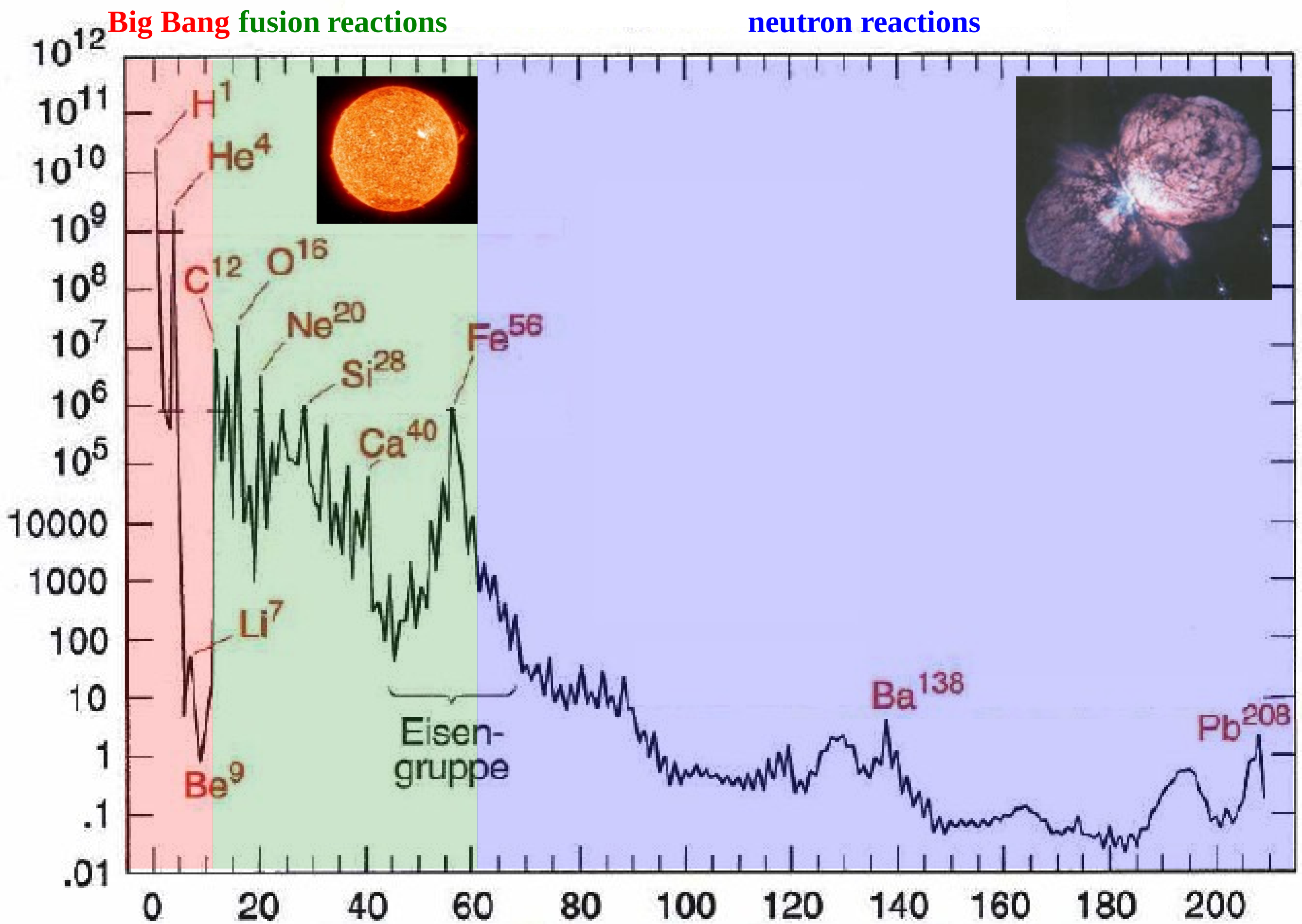
Indicators for nuclear shell model:

high energies of 2_1^+ state

for nuclei with magic numbers

Solar abundances of elements

Solar abundance ($Si^{28} = 10^6$)

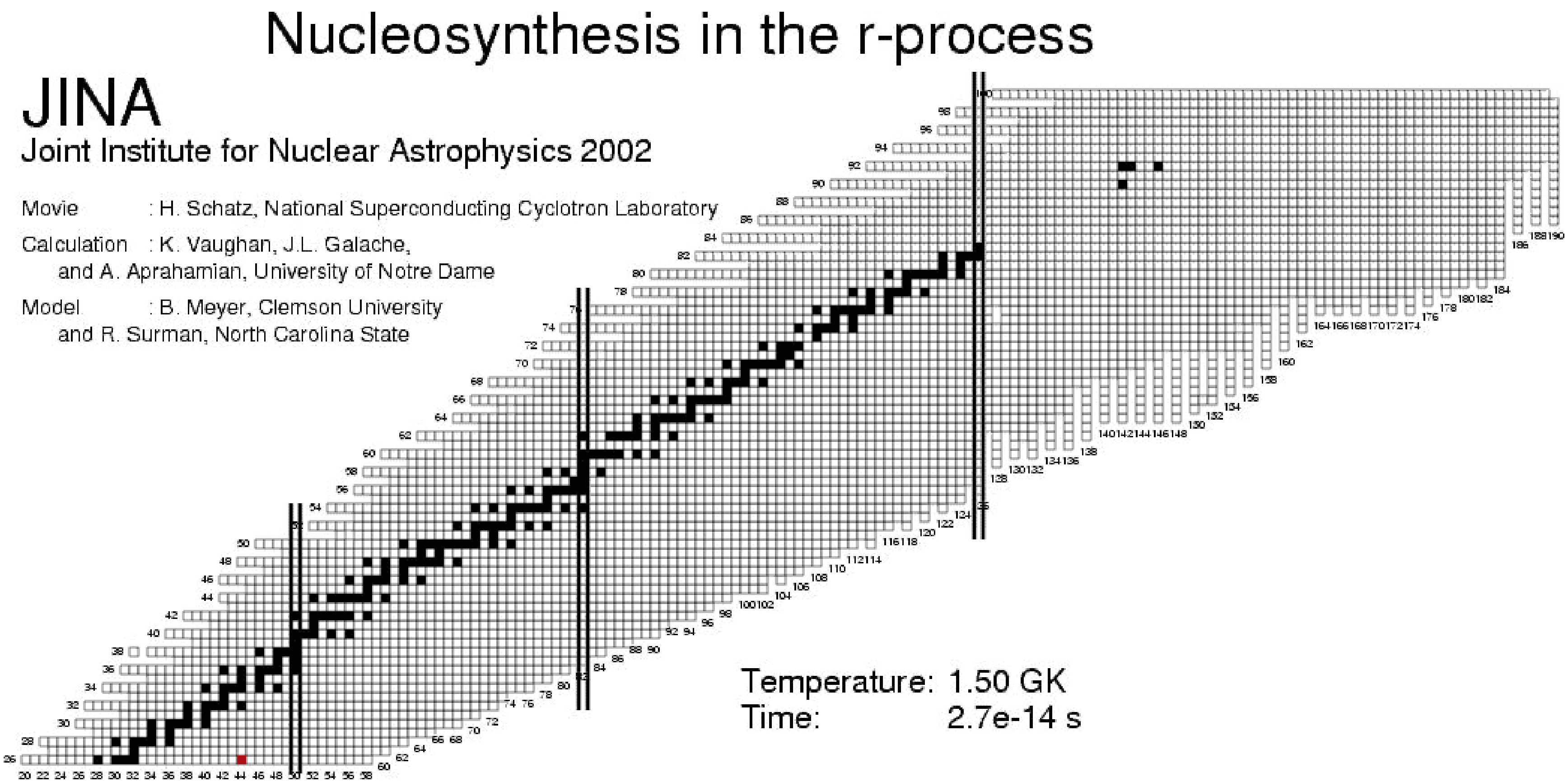


Mass number

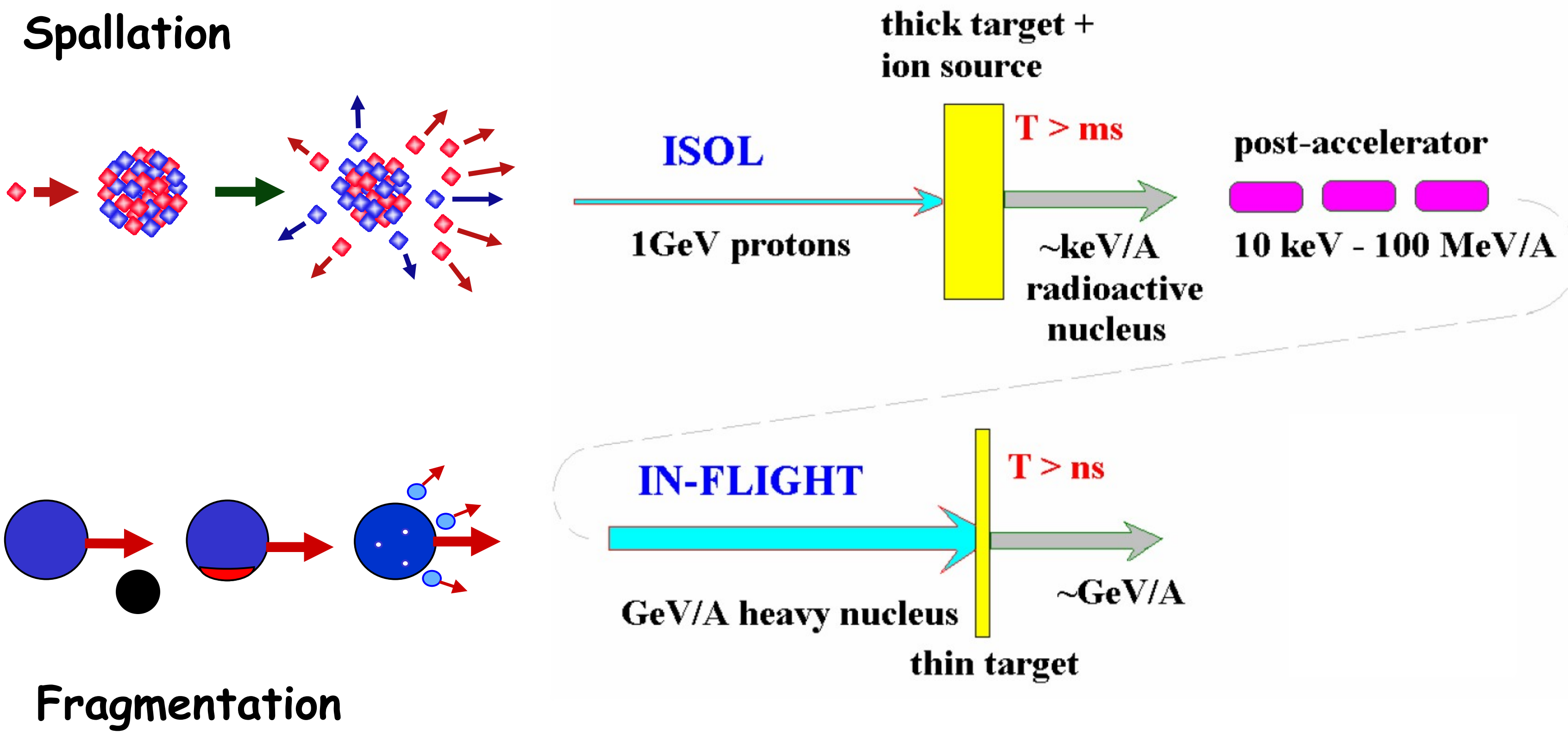
open questions:

- Why is Fe more common than Au ?
- Why do the heavy elements exist and how are they produced?
- Can we explain the solar abundances of the elements?

The chart of nuclides



Spallation & Projectile Fragmentation Reactions
A Route to Exotic Nuclei



ISOL = Isotope Separator On Line

High-energy proton-induced nuclear reactions

Some early high-energy proton accelerators:

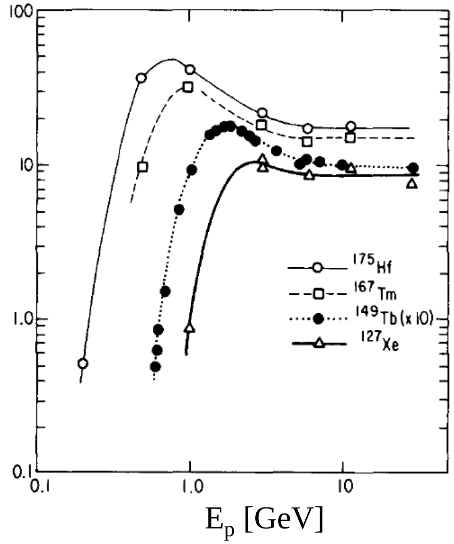
Facility	Energy	from year
Bevatron (Berkeley)	6 GeV	1954.....
AGS (Brookhaven)	11 GeV	1960.....
Fermilab (Chicago)	>300 GeV	1967.....

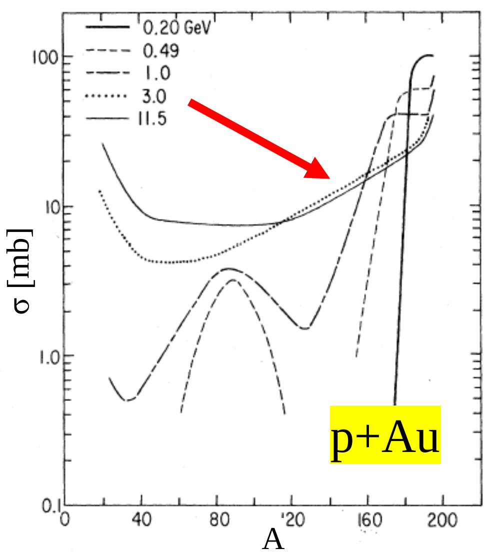
They were also used to bombard various stable target materials.

These targets were analyzed with radiochemical methods,
i.e. γ-spectroscopy with or without chemical separators

➡ Production cross sections and (some) kinematics for suitable radioactive isotopes

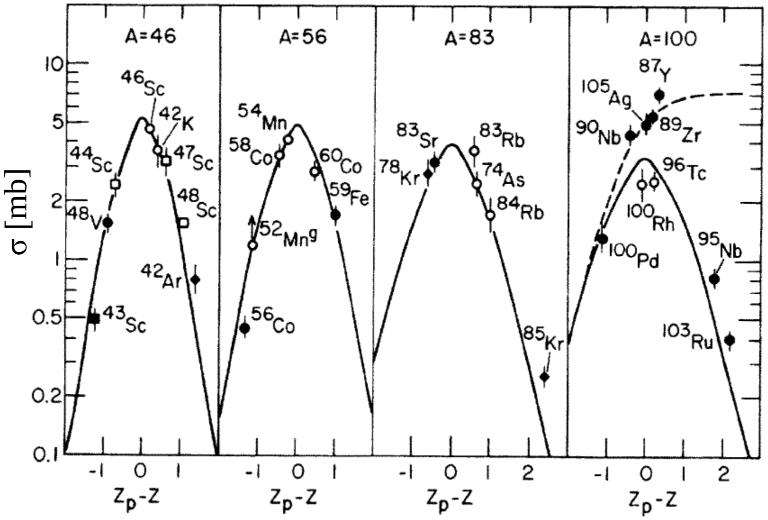
High-energy proton-induced nuclear reactions





Important findings:

- ❖ Energy-independence of cross sections
- ❖ Bell-shaped Z-distribution for constant A



- ❖ Mass yields: exponential slope

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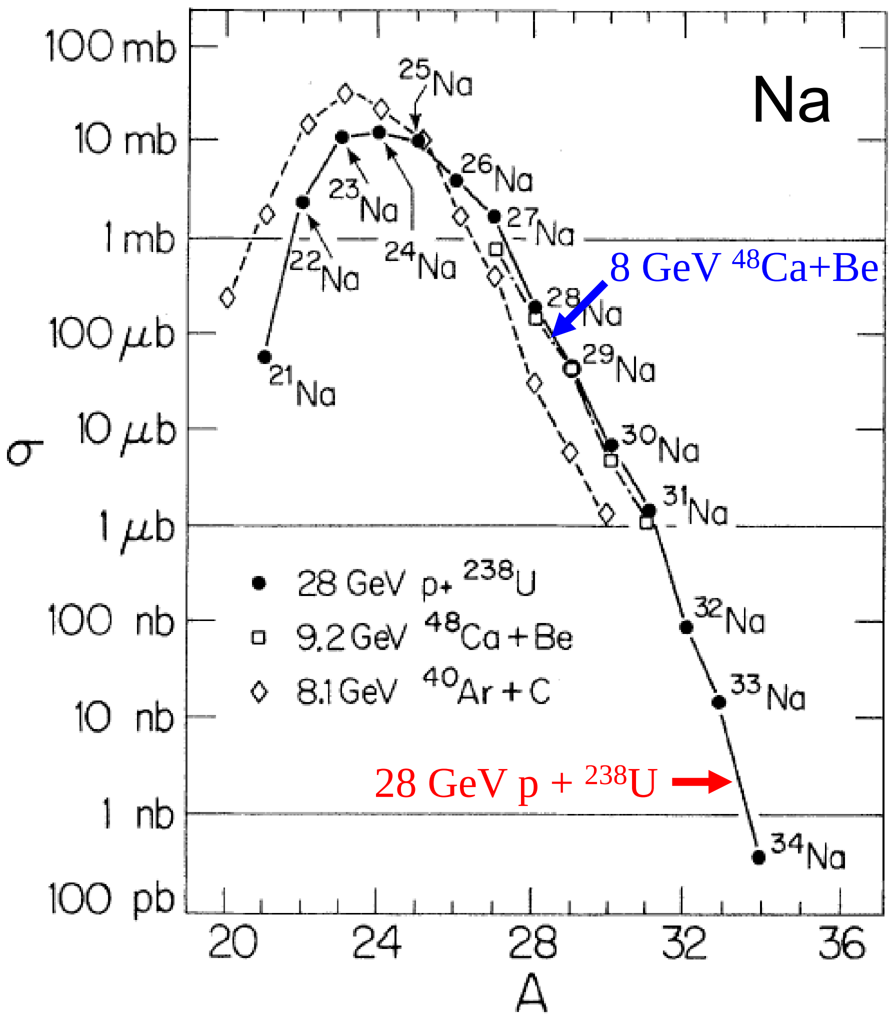
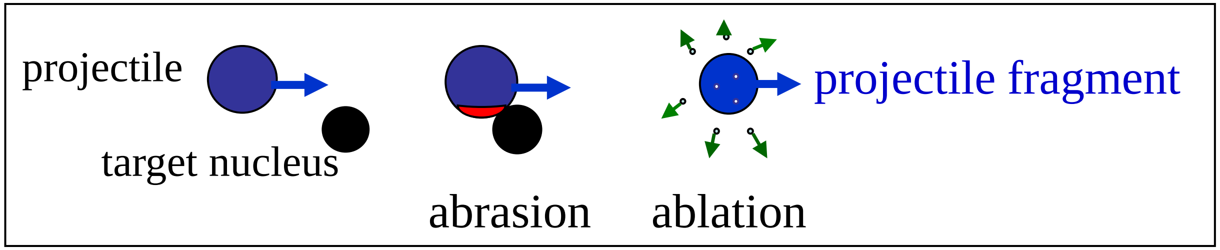
Proton- versus heavy-ion induced reactions

Proton- and heavy-ion induced reactions give very similar isotope distribution:

Target fragmentation:	GeV p + $A_{target} \rightarrow A$
Projectile fragmentation:	GeV/u A_{proj} + p $\rightarrow A$
are equivalent	



Projectile fragmentation reactions



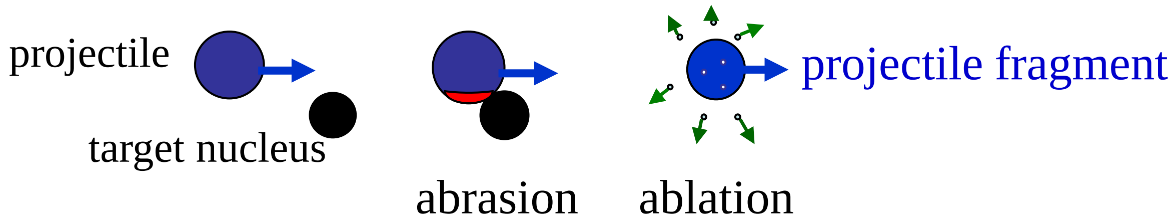
At GeV energies nucleons can be regarded as a classical particles

- Nucleon-nucleon collisions can be treated classically using measured free nucleon-nucleon cross sections (intra-nuclear cascade).
- In these collisions very *little transfer momentum* is exchanged.
- After the cascade the residual nucleus is *highly excited*.
- Heavy-ion projectiles can be treated as a bag of individual nucleons.

Physical models: Two-step approach

Step 1: **Intranuclear-cascade** models or **Abrasion** models
Step 2: **Evaporation** calculation

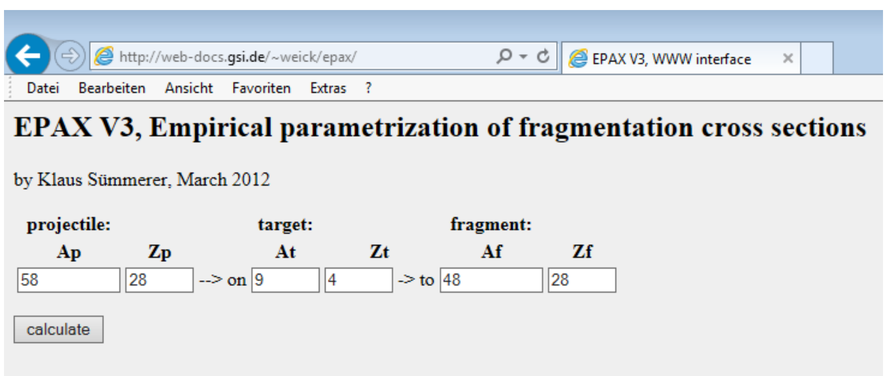
Projectile fragmentation reactions

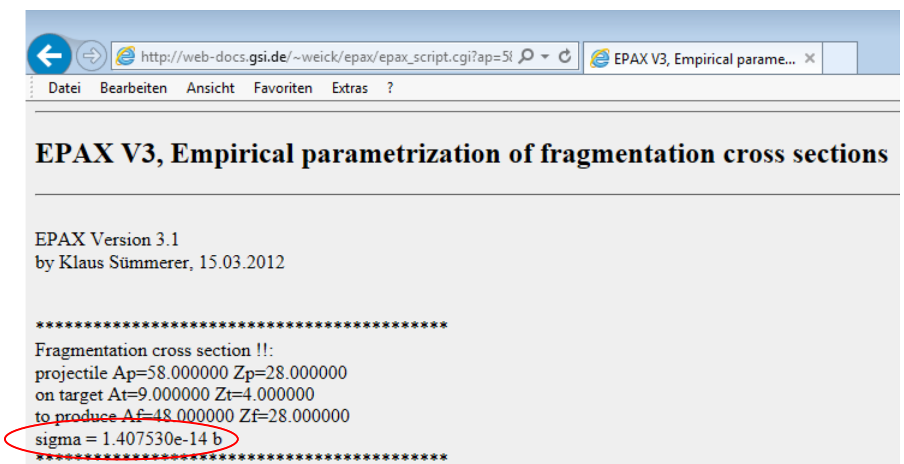


Empirical parameterization of fragmentation cross section:

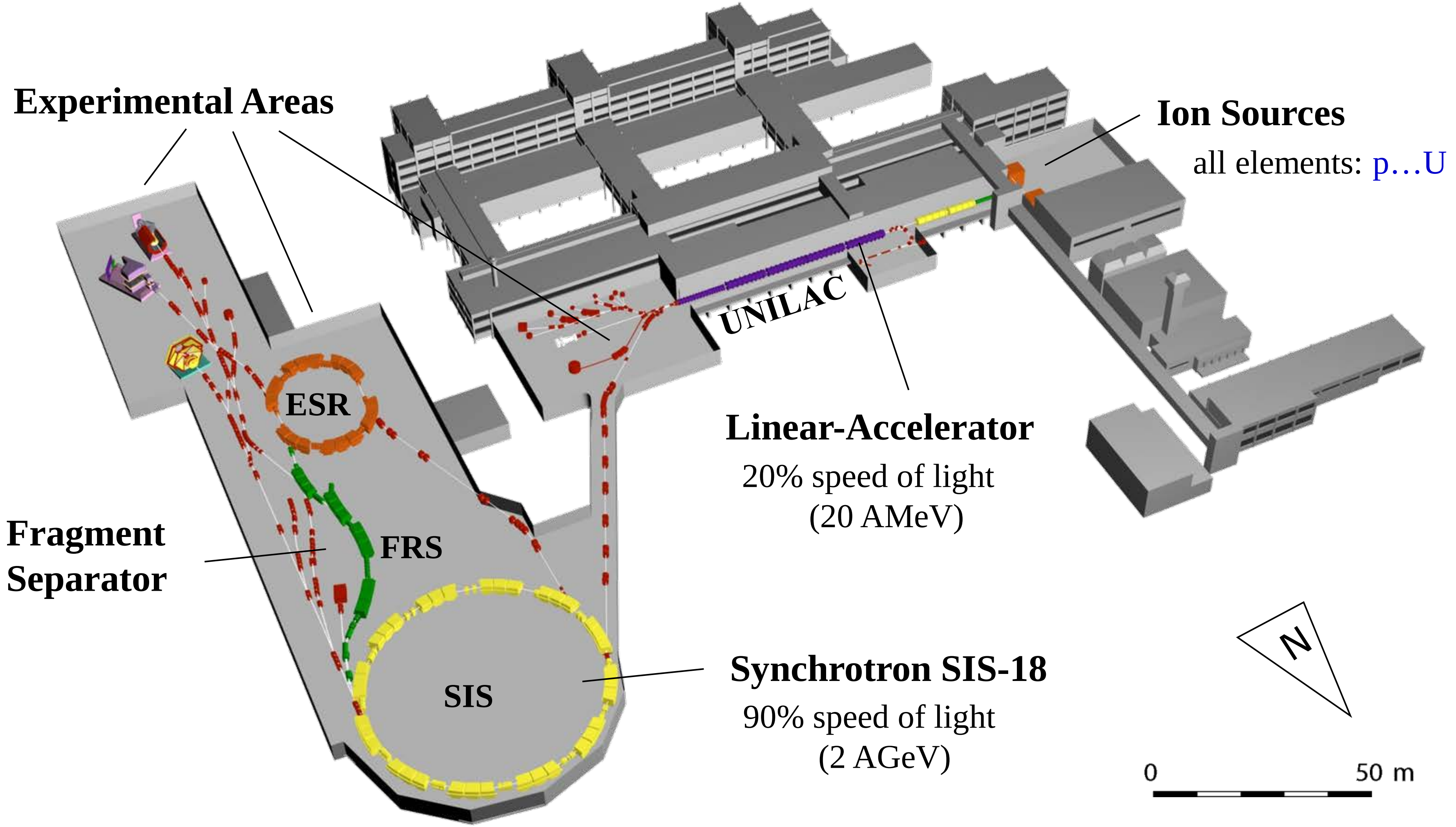
EPAX v.3 K. Sümmerer, Phys. Rev. C86 (2012) 014601

http://web-docs.gsi.de/~weick/epax/

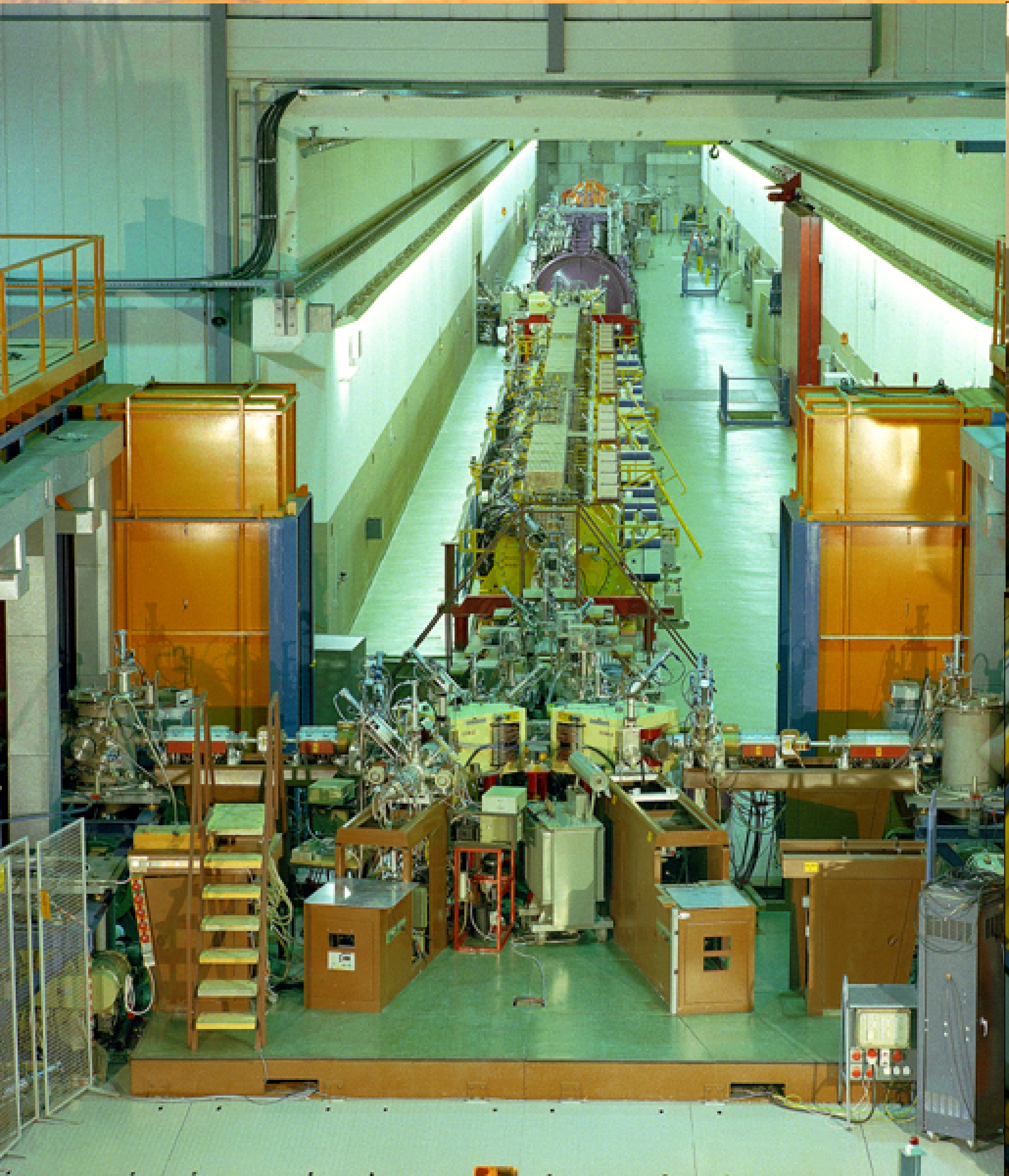


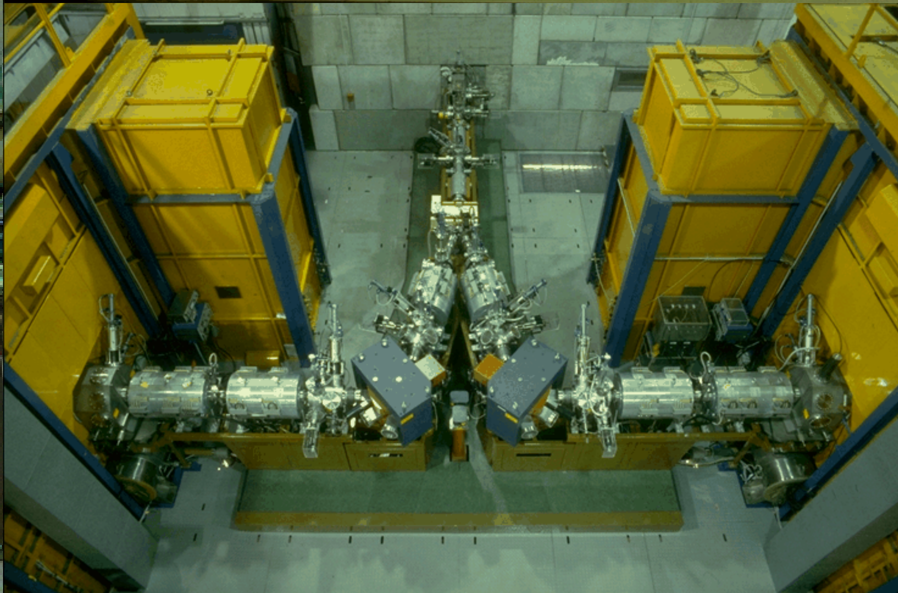


The Accelerator Facility at GSI



UNILAC Accelerator





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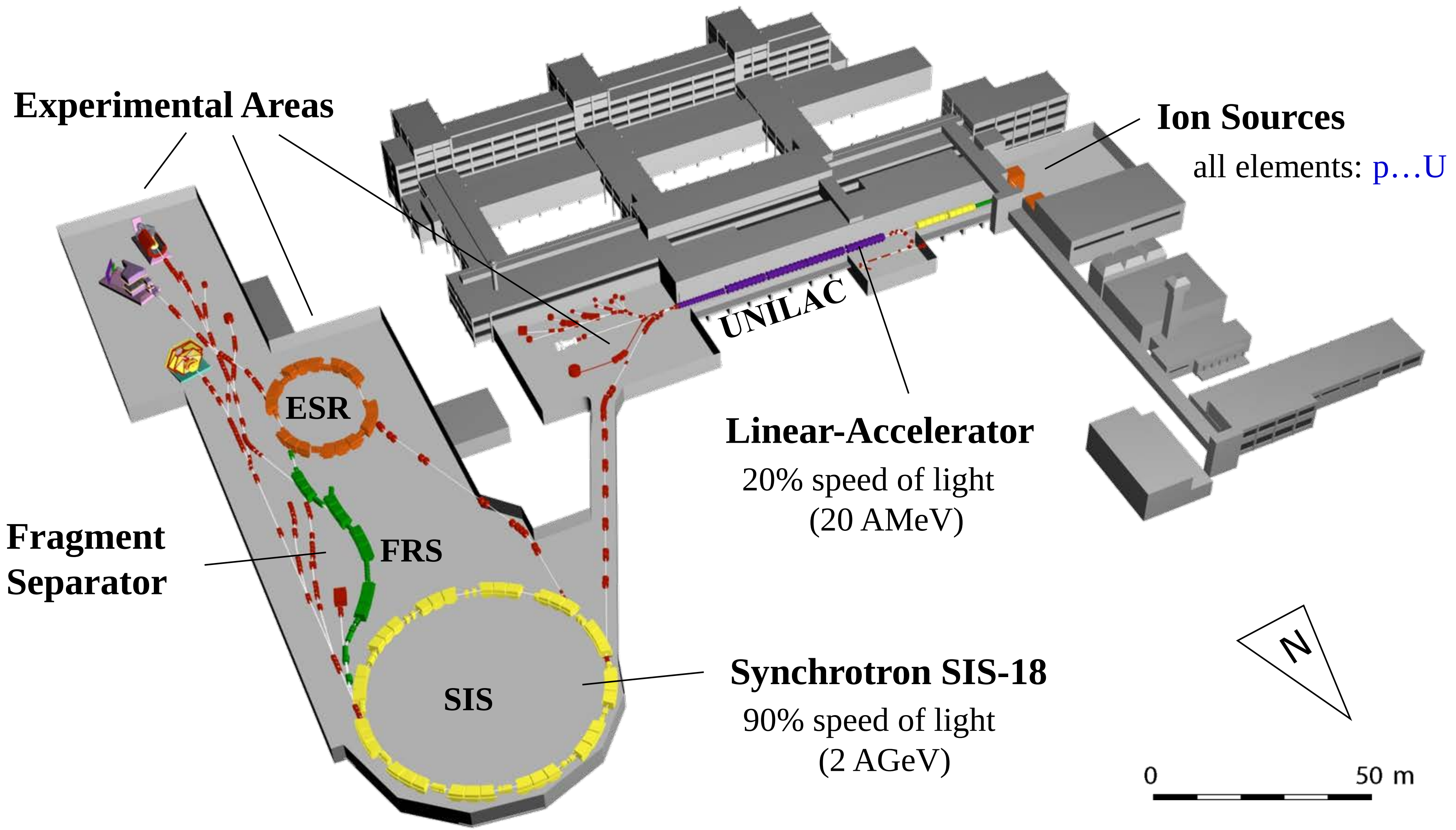
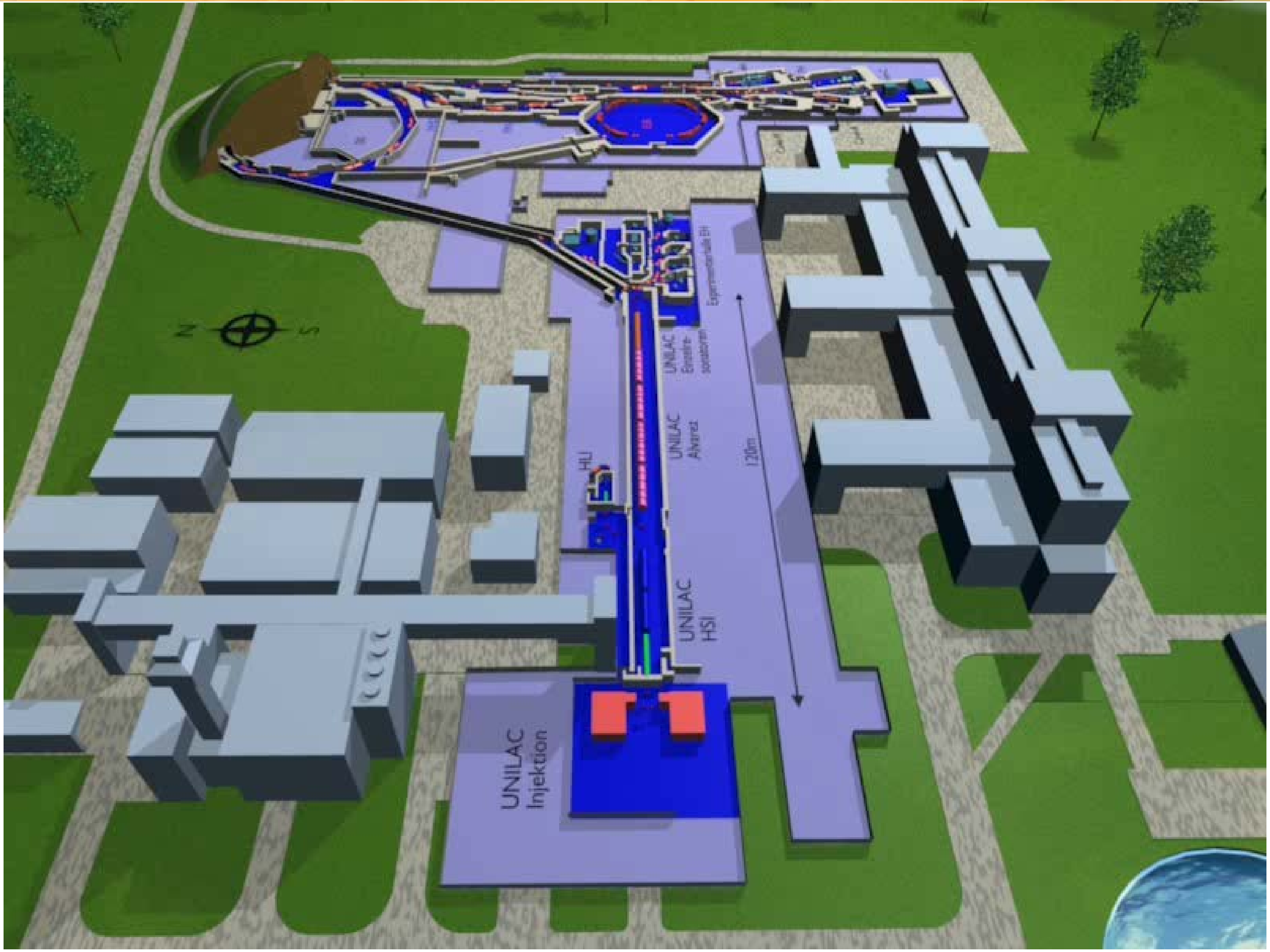
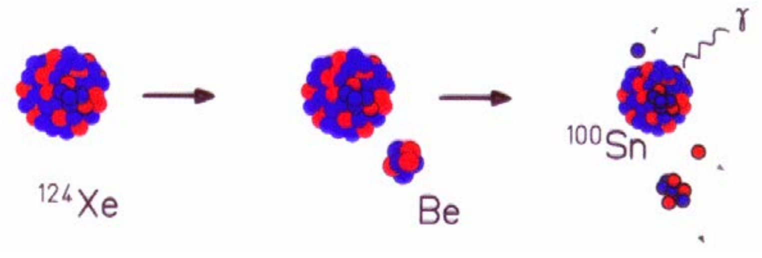


Where do we do the experiments?

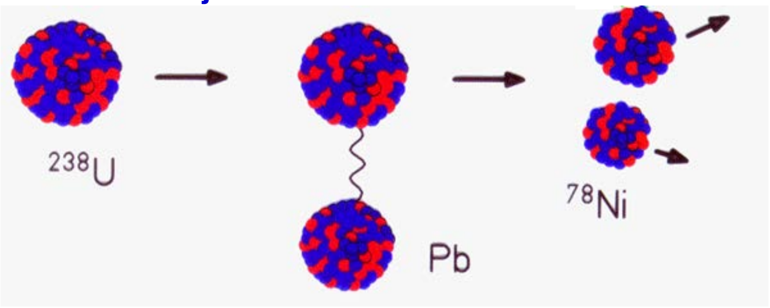


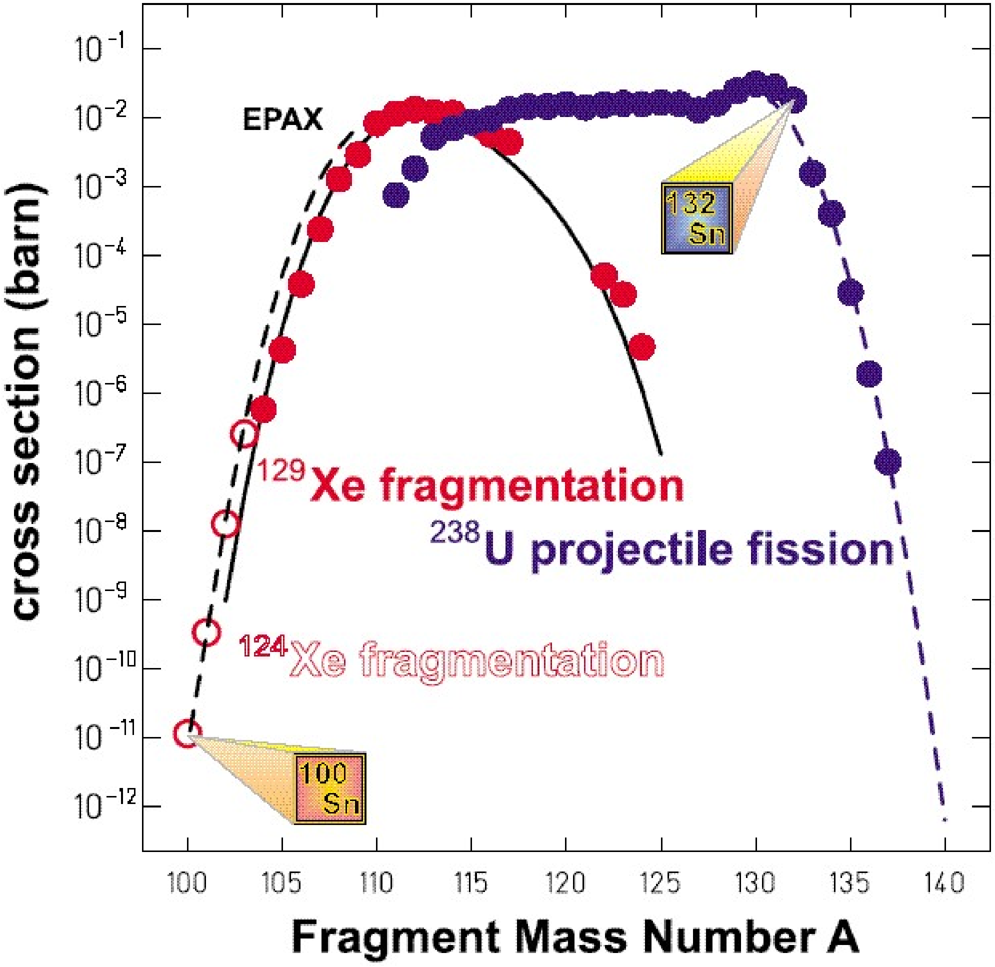
Projectile fragmentation reactions

Projectile Fragmentation



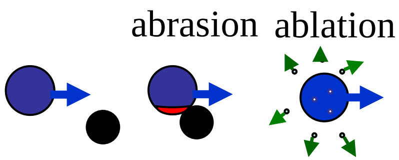
Projectile Fission



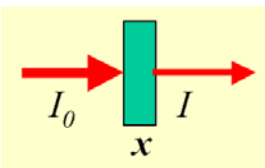


Nuclear Reaction Rate

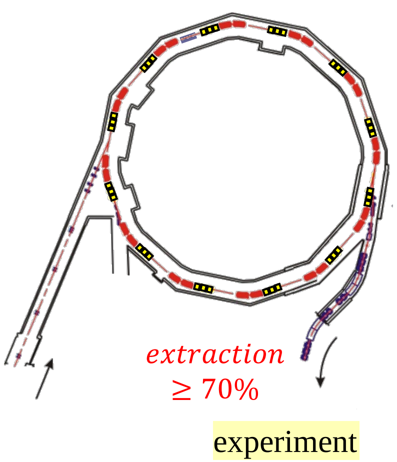
- nuclear reaction rate [s^{-1}] = luminosity [atoms cm^{-2} s^{-1}] * σ_f [cm^2]



- σ_f [cm^2] **for projectile fragmentation + fission**

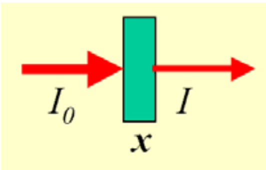


- luminosity [atoms cm^{-2} s^{-1}] = projectiles [s^{-1}] * target nuclei [cm^{-2}]



Ion	SIS-18 (2008)	SIS-100 (expected)	
$^{20}Ne^{10+}$	$2\cdot10^{11}$	$^{20}Ne^{7+}$	$1.6\cdot10^{12}$
$^{40}Ar^{18+}$	$1\cdot10^{11}$	$^{40}Ar^{10+}$	$1.4\cdot10^{12}$
$^{58}Ni^{26+}$	$9\cdot10^{10}$	$^{58}Ni^{14+}$	$1.3\cdot10^{12}$
$^{84}Kr^{34+}$	$8\cdot10^{10}$	$^{84}Kr^{17+}$	$1.2\cdot10^{12}$
$^{132}Xe^{48+}$	$7\cdot10^{10}$	$^{132}Xe^{22+}$	$1.3\cdot10^{12}$
$^{197}Au^{65+}$	$5\cdot10^{10}$	$^{197}Au^{25+}$	$1.2\cdot10^{12}$
$^{238}U^{73+}$	$1.6\cdot10^{10}$	$^{238}U^{92+}$	$1.4\cdot10^{10}$
$^{238}U^{28+}$	$1.4\cdot10^{10}$	$^{238}U^{28+}$	$5.0\cdot10^{11}$

Nuclear Reaction Rate



density ρ

Primary reaction rate:

$$\phi_f\left[s^{-1}\right] \cong \phi_p\left[s^{-1}\right] \cdot \frac{x\left[g/cm^2\right] \cdot 6.02 \cdot 10^{23}}{A_t[g]} \cdot \sigma_f\left[cm^2\right]$$

(thin target)

Example: ^{238}U ($10^9 s^{-1}$) on ^{208}Pb (x=1g/cm²) ⟶ ^{132}Sn (σ_f=15.4mb) reaction rate: 44571 [s^{-1}]

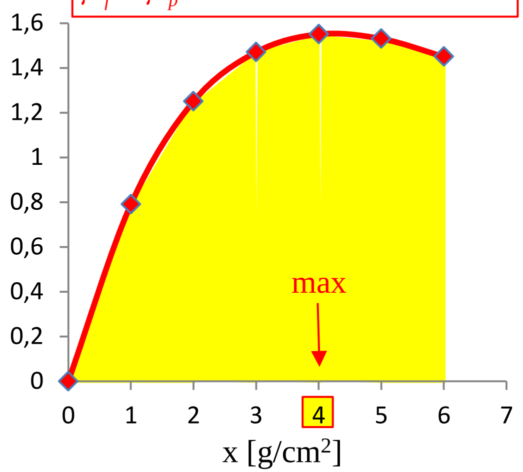
Example: ^{124}Xe ($10^9 s^{-1}$) on ^{9}Be (x=1g/cm²) ⟶ ^{104}Sn (σ_f=5.6μb) reaction rate: 375 [s^{-1}]

The ***optimum thickness*** of the production target is limited by the loss of fragments due to secondary reactions

Primary + secondary reaction rate:

$$\phi_f\left[s^{-1}\right] = \phi_p\left[s^{-1}\right] \cdot \frac{6.02 \cdot 10^{23} \cdot \sigma_f\left[cm^2\right]}{A_t[g]} \cdot \frac{1}{\mu_f - \mu_p} \cdot \left(e^{-\mu_p \cdot x\left[g/cm^2\right]} - e^{-\mu_f \cdot x\left[g/cm^2\right]}\right)$$

$$\frac{1}{\mu_f - \mu_p} \cdot \left(e^{-\mu_p \cdot x\left[g/cm^2\right]} - e^{-\mu_f \cdot x\left[g/cm^2\right]}\right)$$



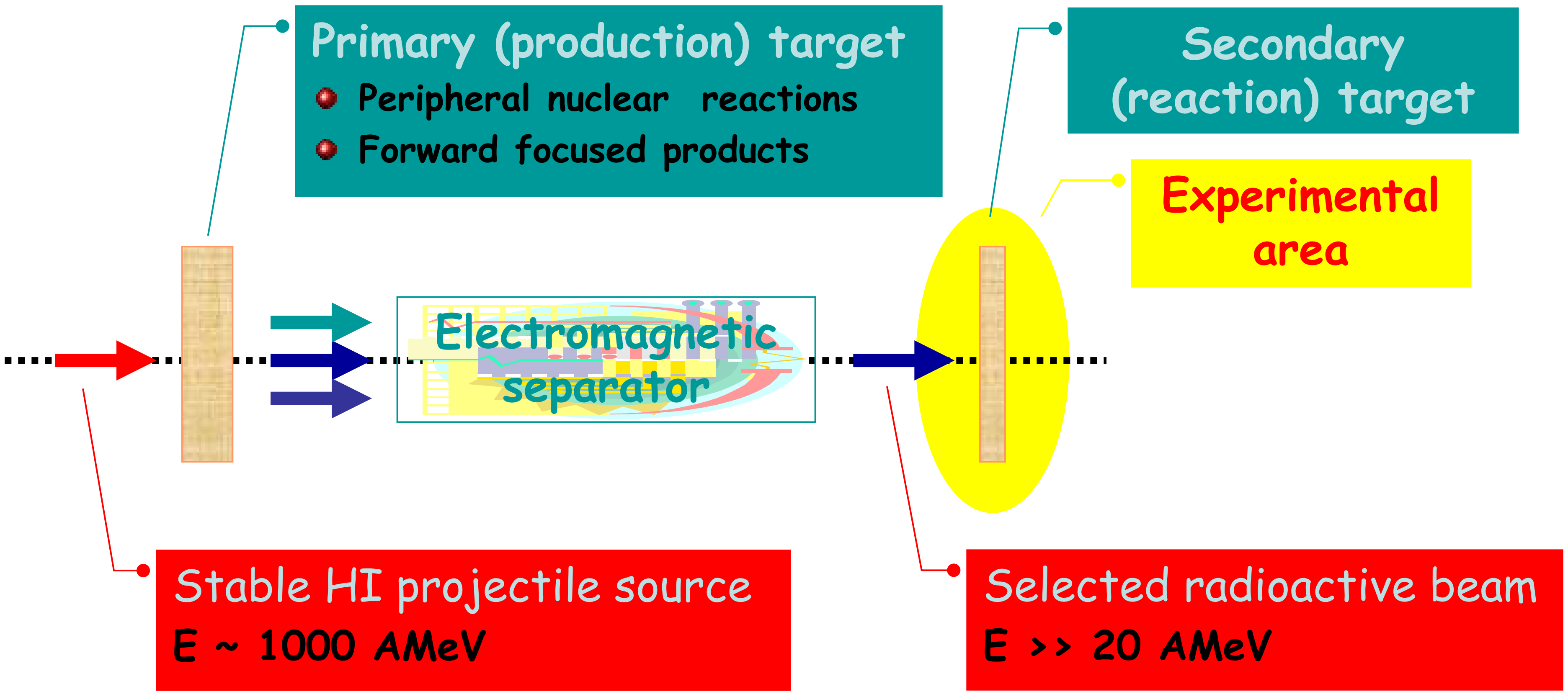
with $$\mu = \frac{6.02 \cdot 10^{23}}{A_2[g]} \cdot \sigma_{reaction}\left[cm^2\right]$$

Example: ^{124}Xe *on* $^{9}Be \rightarrow {}^{104}Sn$, $\sigma(^{124}Xe + {}^{9}Be) = 3.65[b] \rightarrow \mu_p = 0.244\left[cm^2/g\right]$

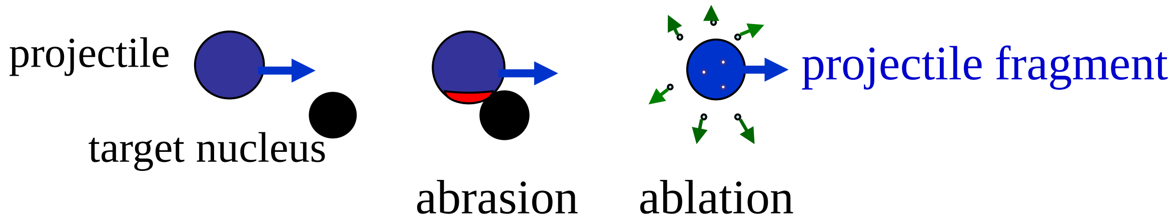
$\sigma(^{104}Sn + {}^{9}Be) = 3.44[b] \rightarrow \mu_f = 0.230\left[cm^2/g\right]$

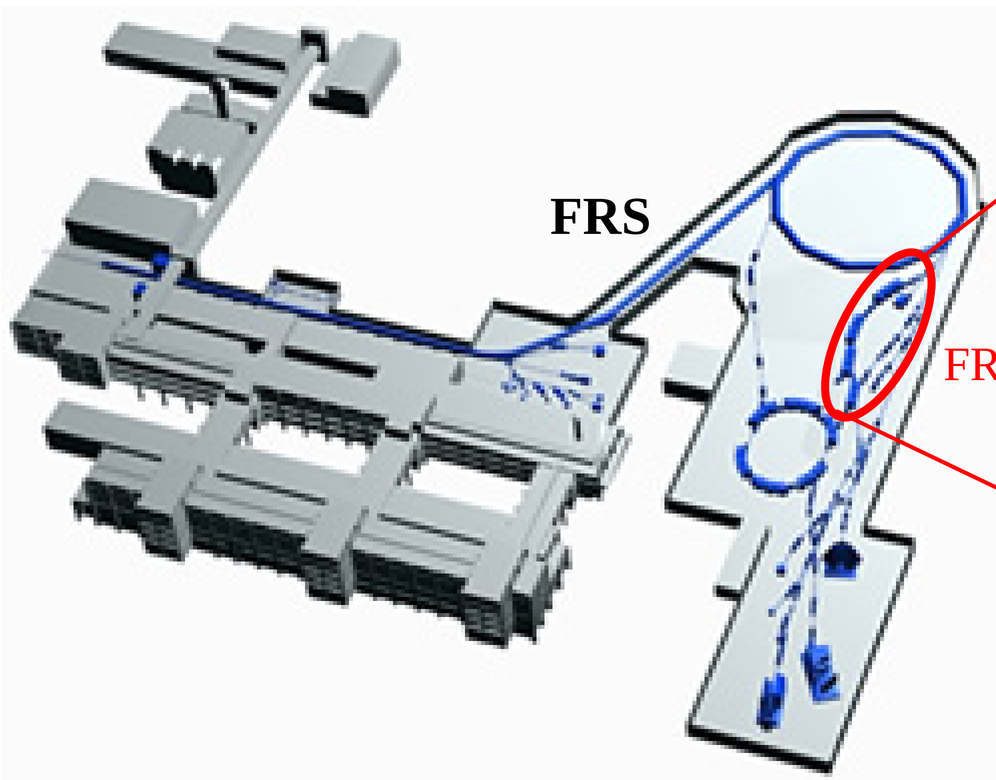
$$\phi_f[s^{-1}] = \phi_p[s^{-1}] - \phi[s^{-1}] = \phi_p[s^{-1}] \cdot \left\{1 - e^{-N_t[cm^{-2}] \cdot \sigma_f[cm^2]}\right\}$$ (thick target)

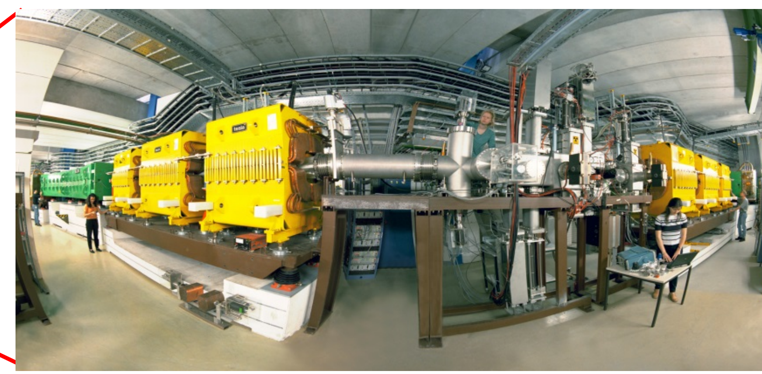
In-Flight Separation of Radioactive Ion Beams



Fragmentation at Relativistic Energies

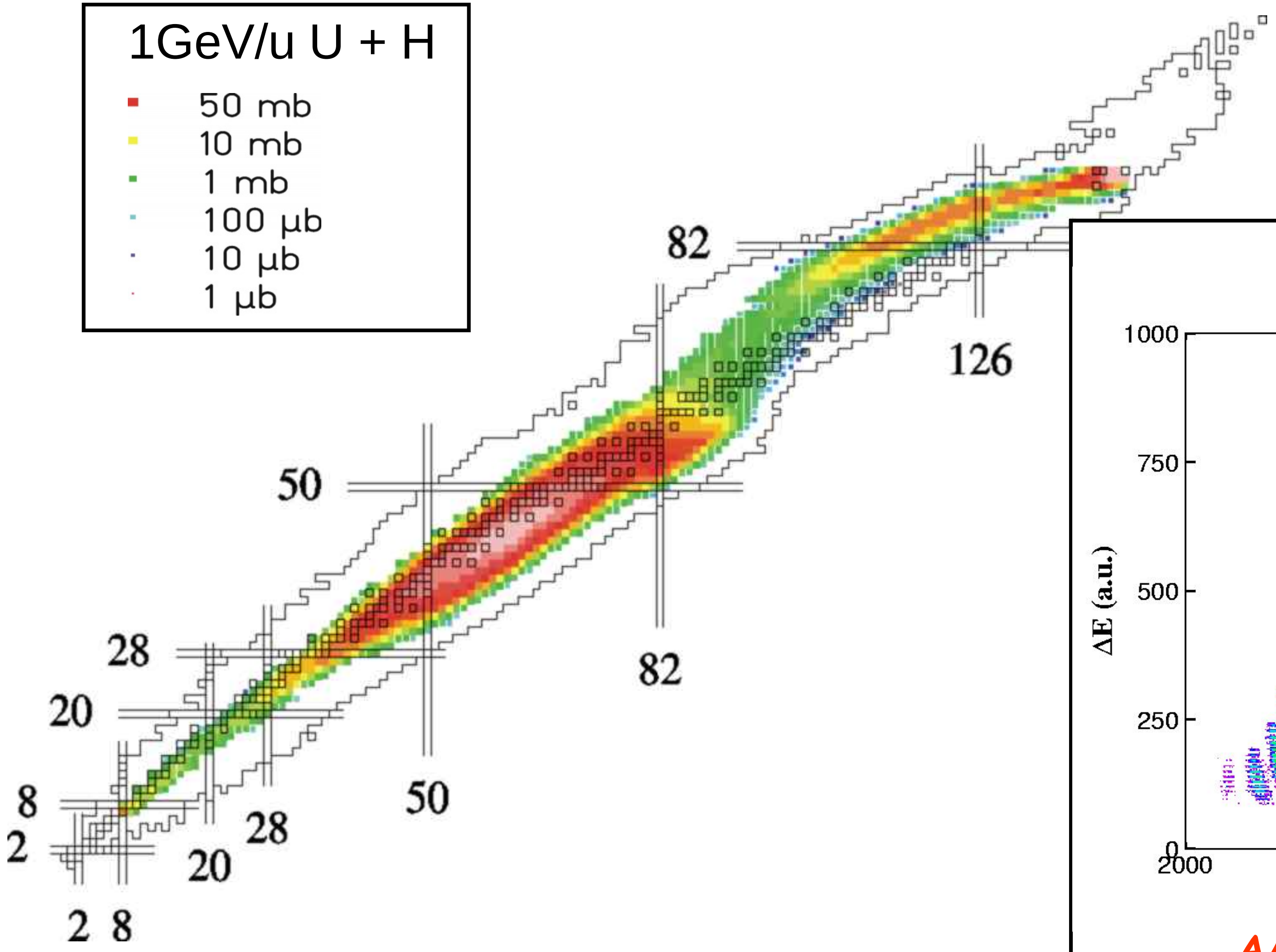


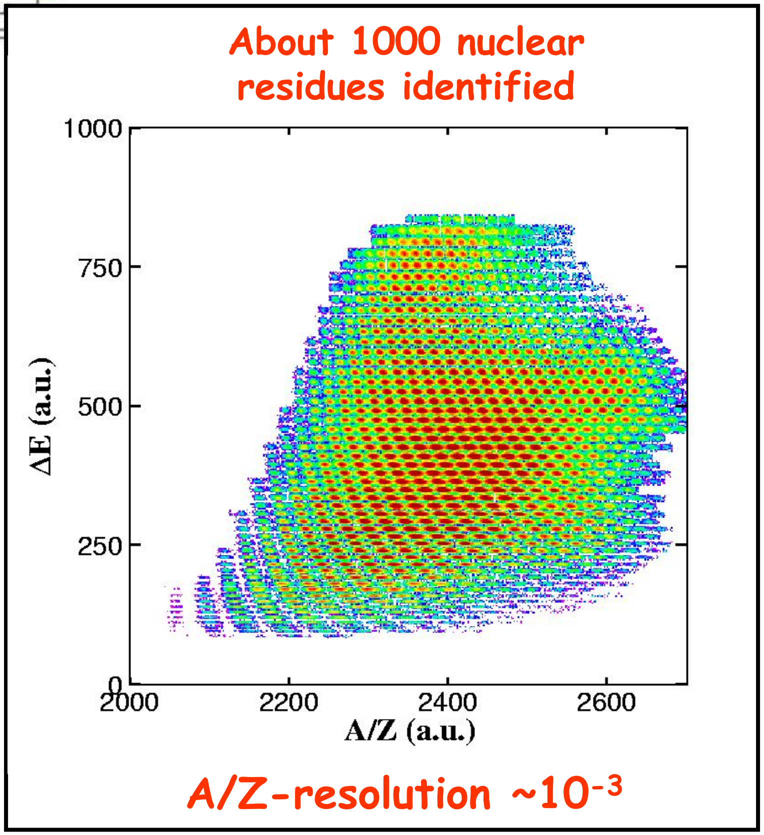




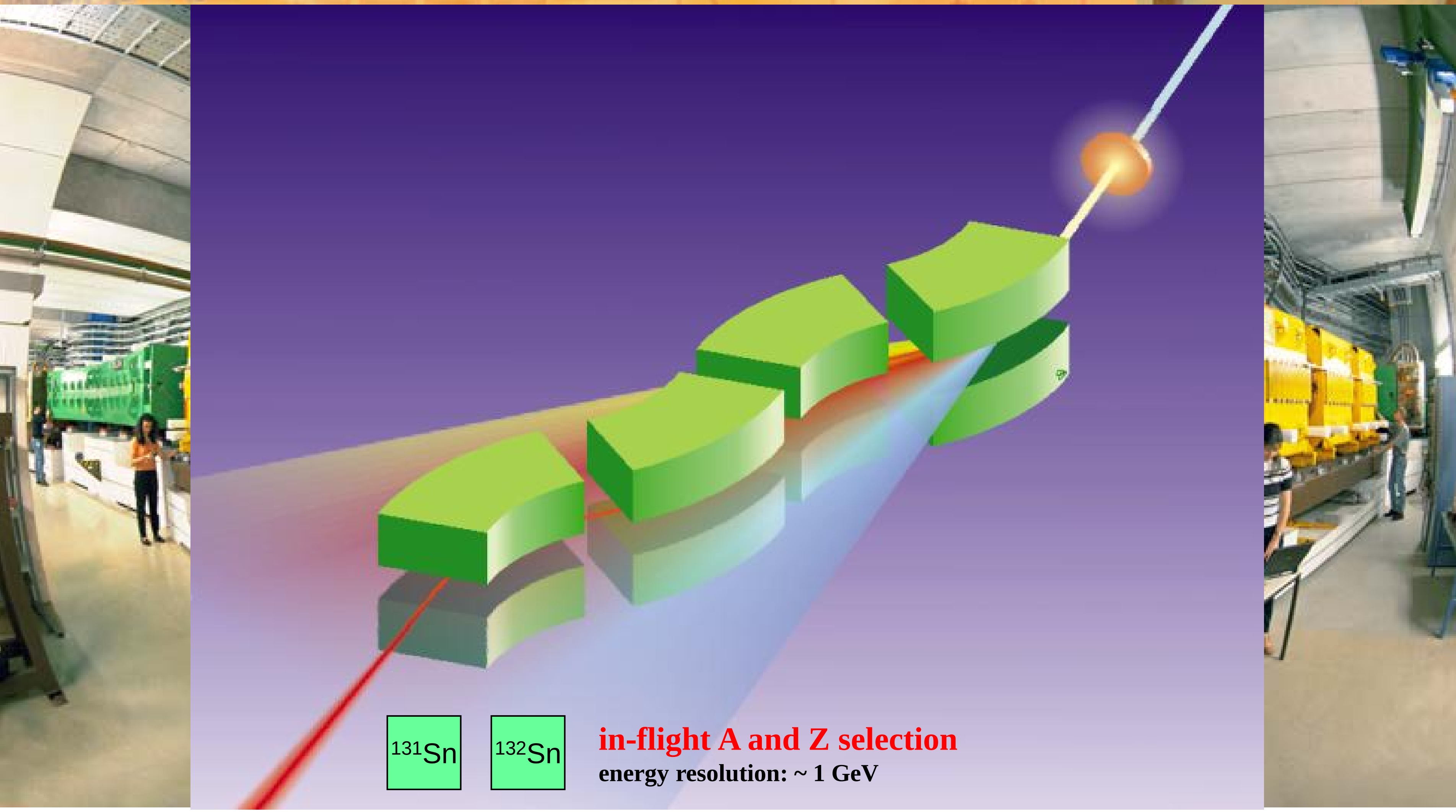
FRagment **S**eparator

Radioactive Ion Beams at GSI





FRagment Separator at GSI



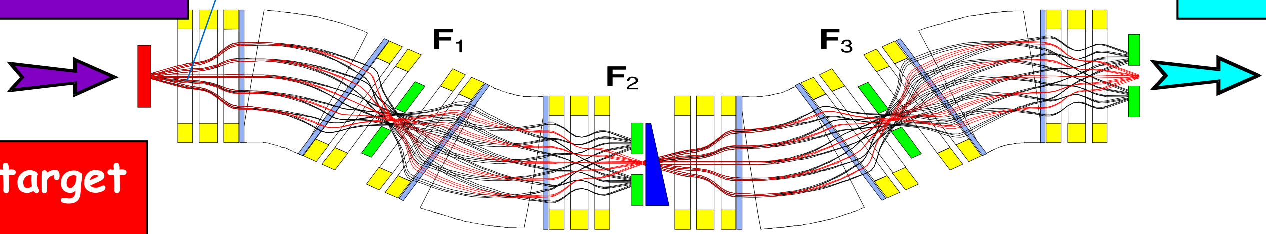
Rare Isotope Selection at FRS: Bρ-ΔE-Bρ Selection

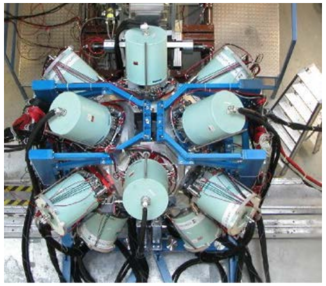
primary beam
^{86}Kr ~700 AMeV

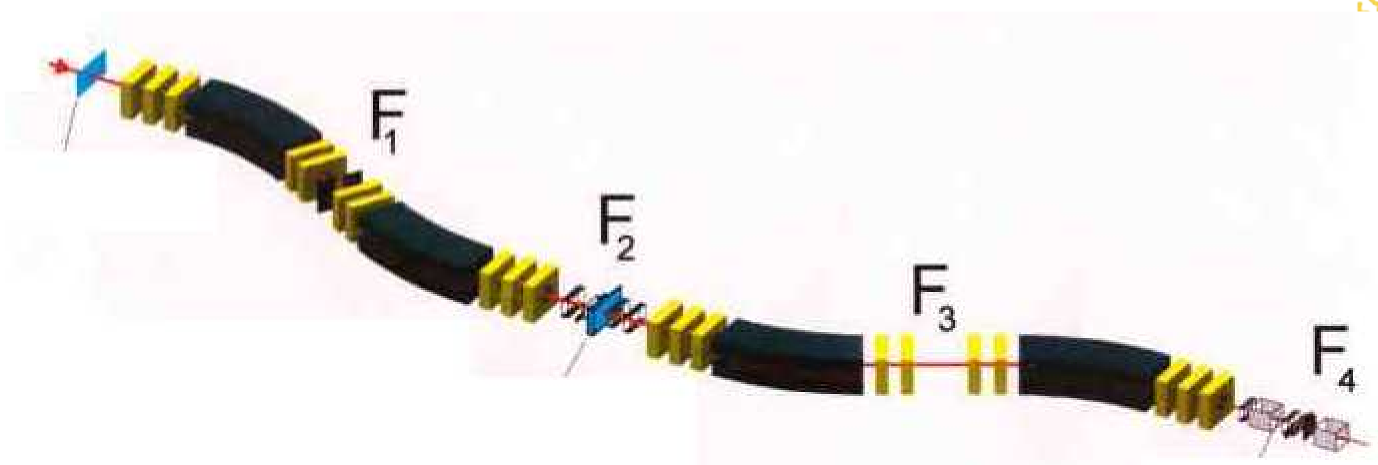
fully striped fragments

production target
^{9}Be

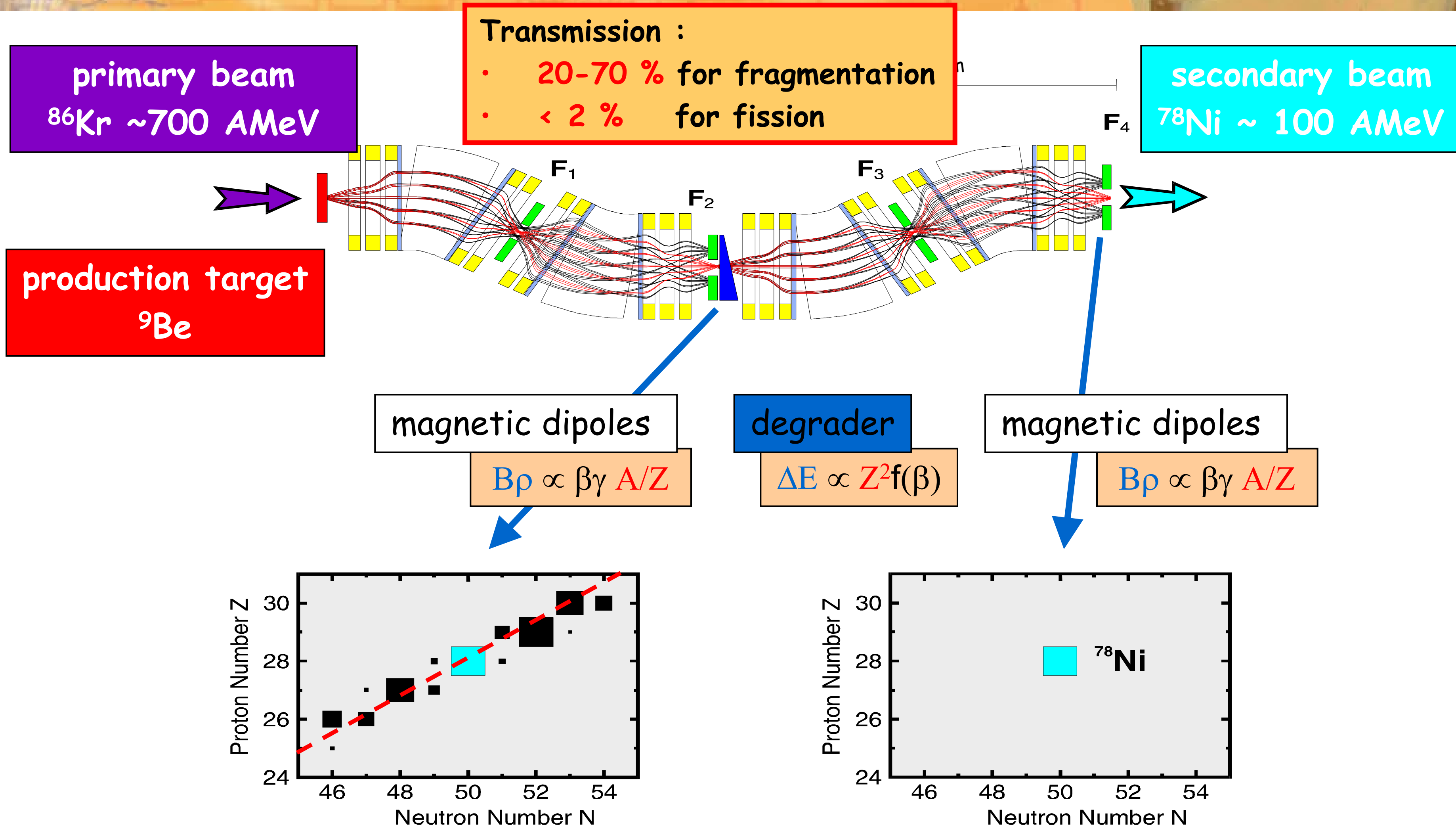
secondary beam
^{78}Ni ~ 100 AMeV



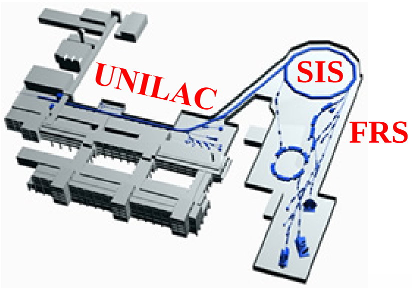


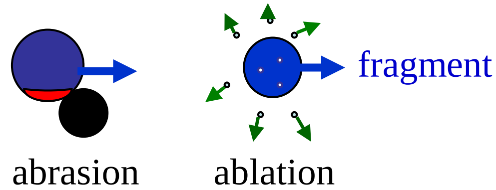


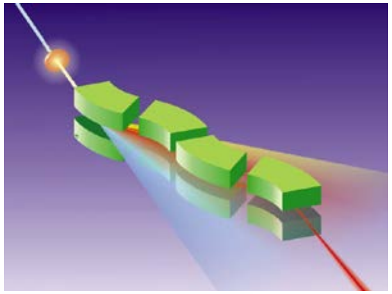
Rare Isotope Selection at FRS: Bρ-ΔE-Bρ Selection



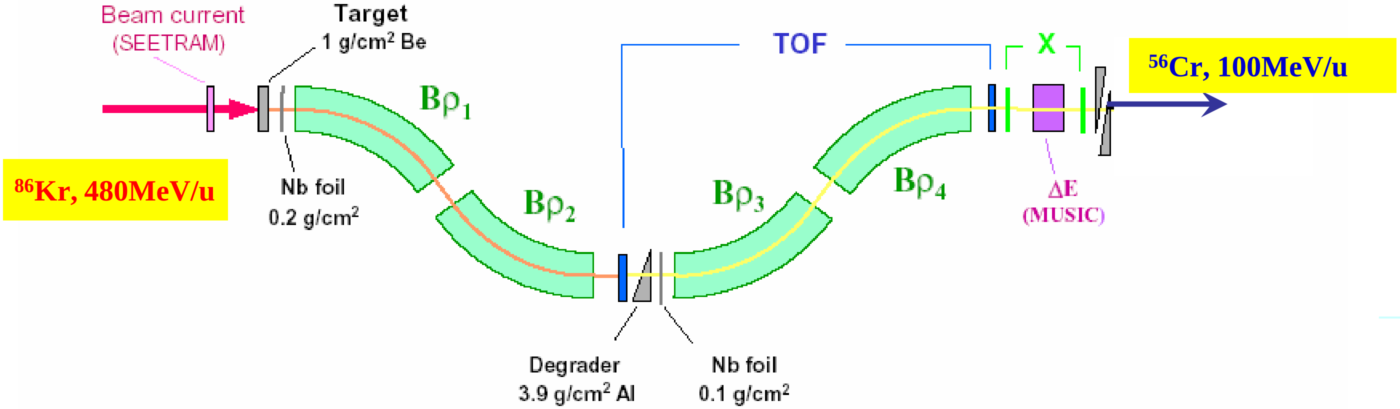
Production, Separation, Identification





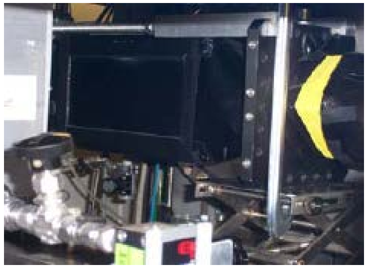


FRagment **S**eparator

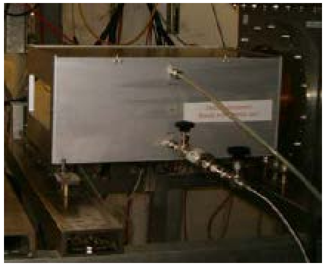


Standard FRS detectors

TPC-**x,y position** @ S2,S4



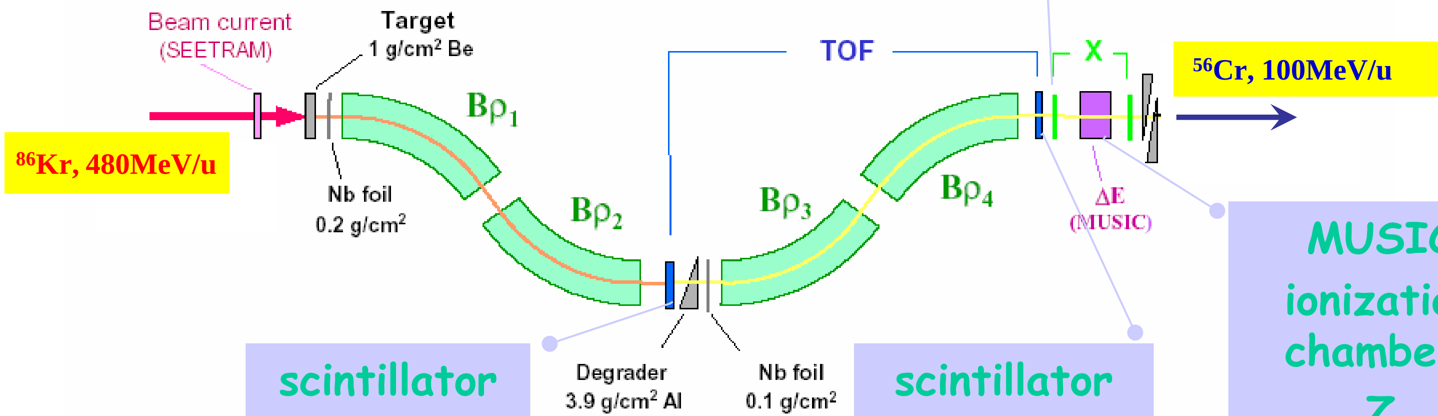
Plastic scintillator (**TOF**) @ S4



MUSIC (**ΔE**) @ S4

Production, Separation, Identification

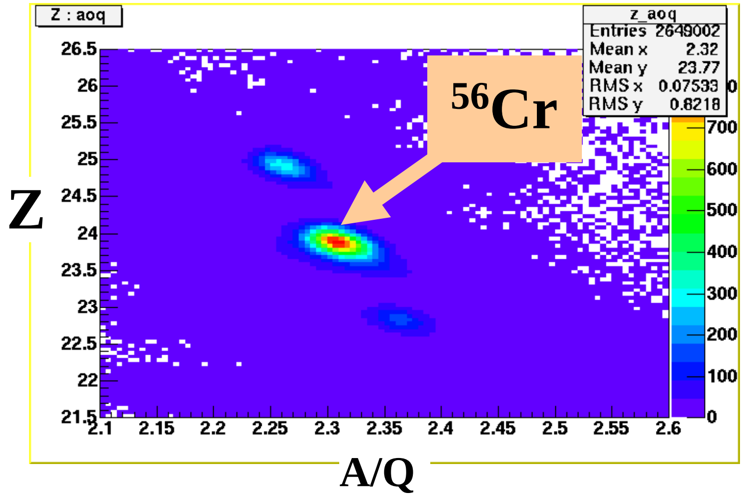
multiwire chamber or TPC; beam position

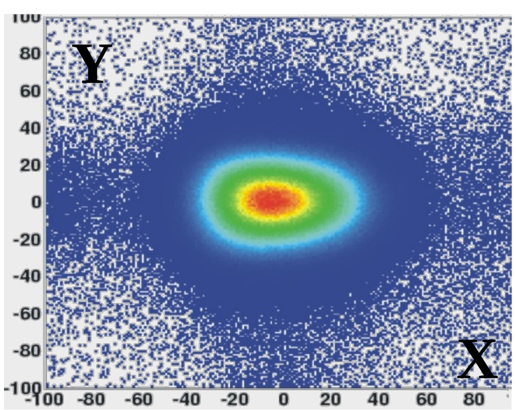


scintillator

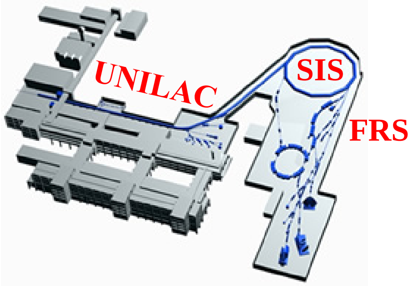
scintillator β

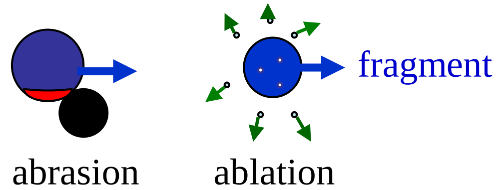
MUSIC ionization chamber; Z

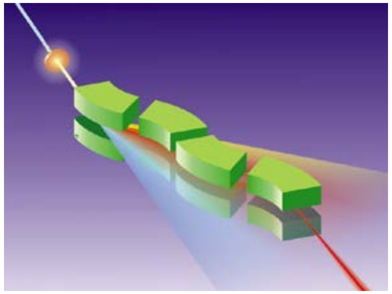




Production, Separation, Identification

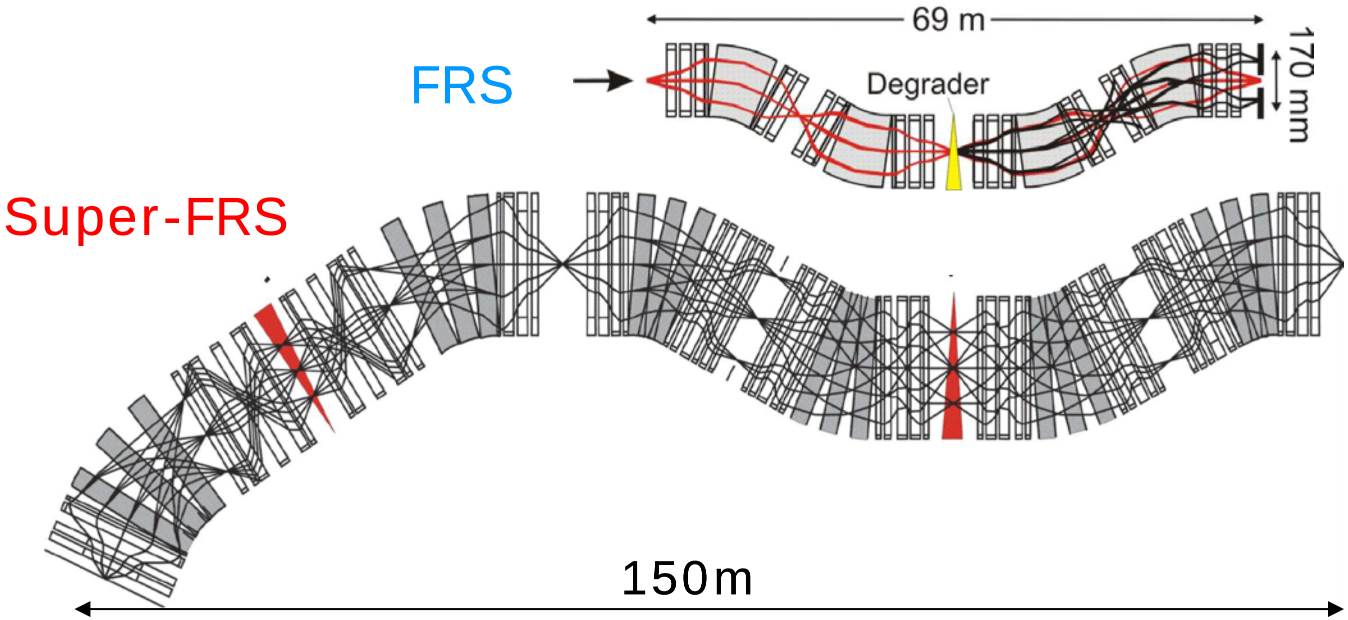


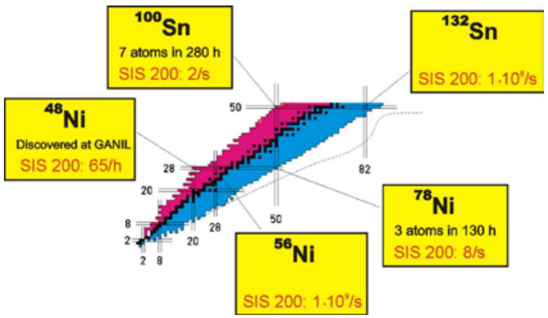




FRagment
Separator

Comparison of FRS with Super-FRS





	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x, \Delta\Phi_y$	resolving power	gain factor ^{19}C	^{132}Sn
FRS	18 Tm	1.0 %	± 13, ±13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500	5	10
				including primary rate	250	20 000