Fasci Radioattivi

Metodi di Produzione: In-Flight, ISOL

FASCI RADIOATTIVI
(ioni con nuclei Esotici)

Ioni instabili prodotti artificialmente(ovvero non esistenti in natura) con caratteristiche energetiche e spaziali tali da poter essere riutilizzati o come sorgente per un acceleratore o come un "normale" fascio ottenuto da un acceleratore per studiarne le proprieta' o produrre reazioni.

- Λ (10^{-10}sec)
- Ξ (10^{-10}sec)
- Li^{11} (neutron rich)
- Sn^{107} (proton-rich)

Cos'e' un nucleo esotico?

Normal Nucleus:

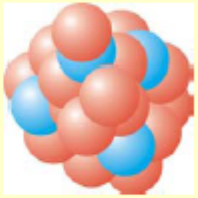
6 neutrons

6 protons (carbon)

^{12}C

Stable, found in nature

Exotic Nucleus:



16 neutrons

6 protons (carbon)

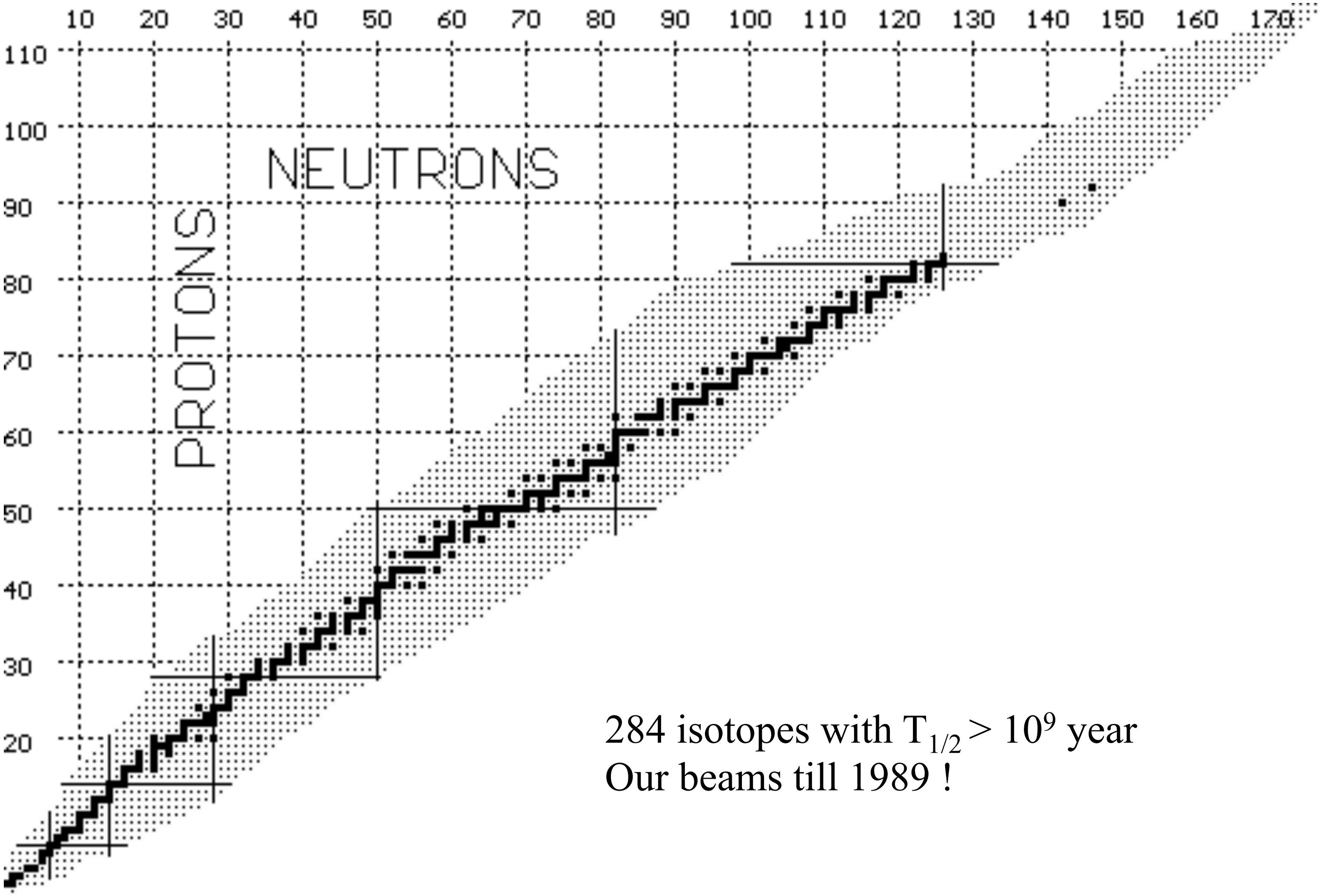
^{22}C

Radioactive, at the limit of nuclear binding

Characteristics of exotic nuclei:

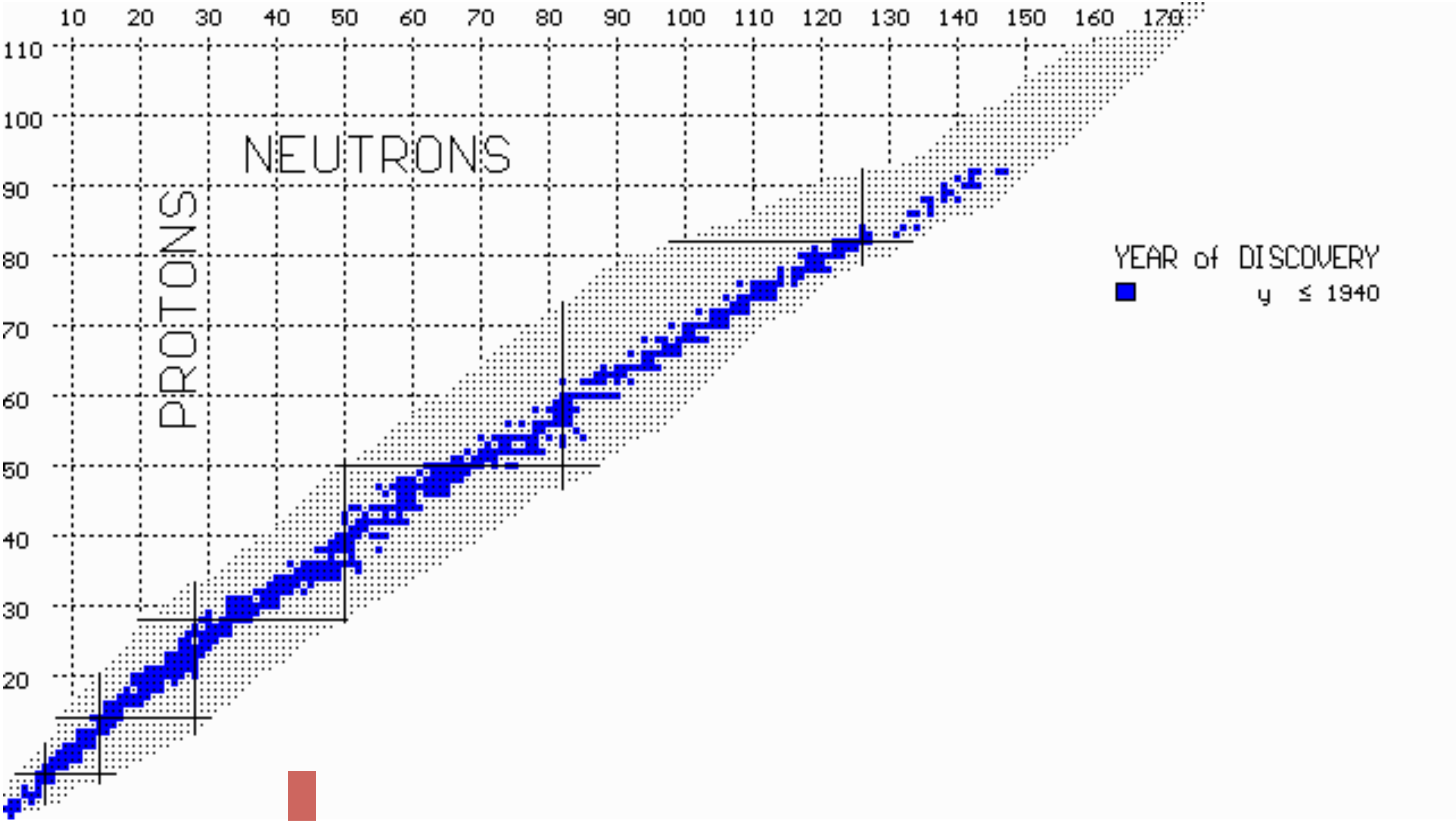
- Excess of neutrons or protons,
- short half-life,
- neutron or proton dominated surface,
- low binding

Un po’ di Storia…



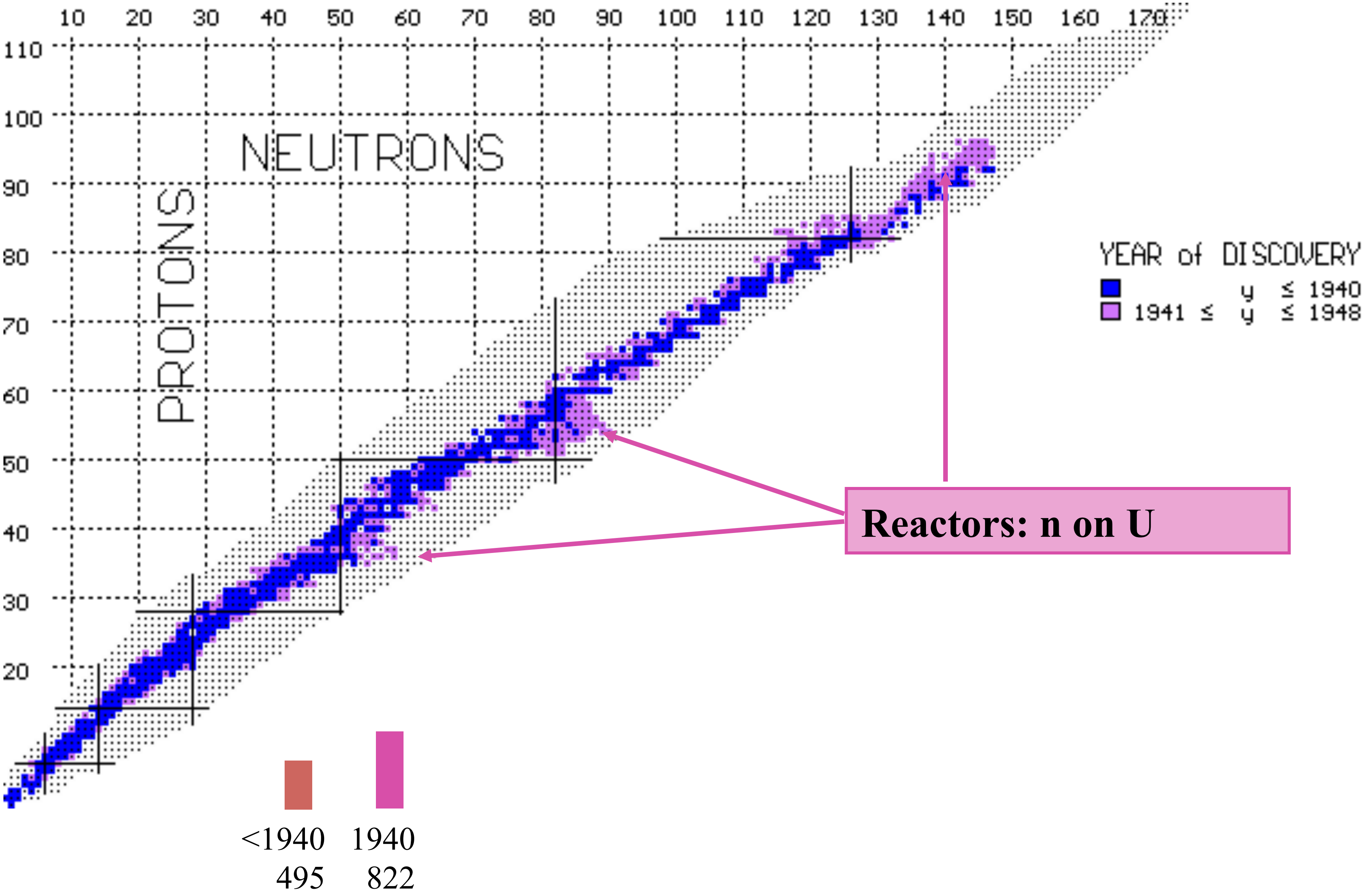
284 isotopes with $T_{1/2} > 10^9$ year
Our beams till 1989 !

Un po’ di Storia…



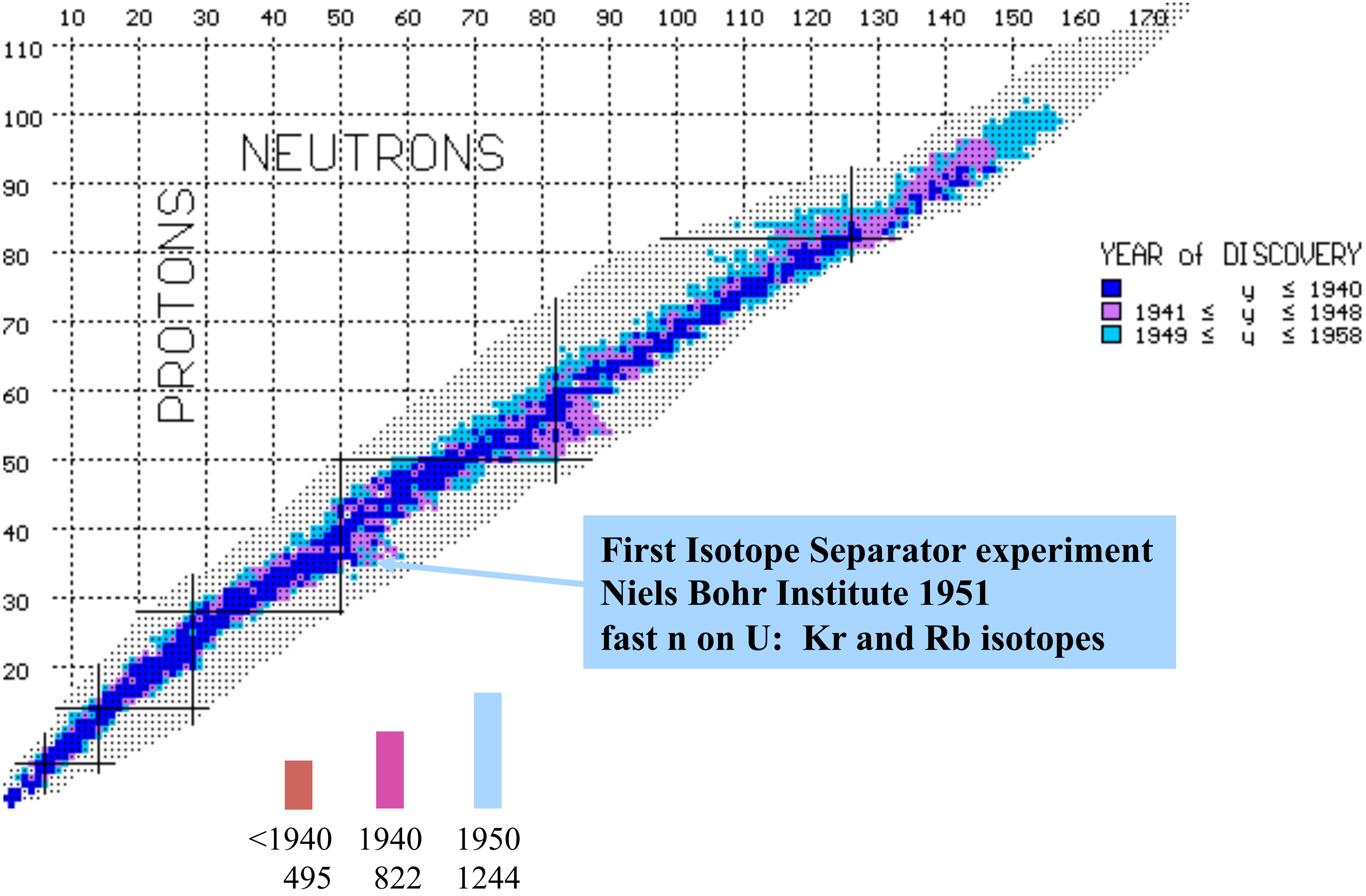
<1940
495

Un po' di Storia…



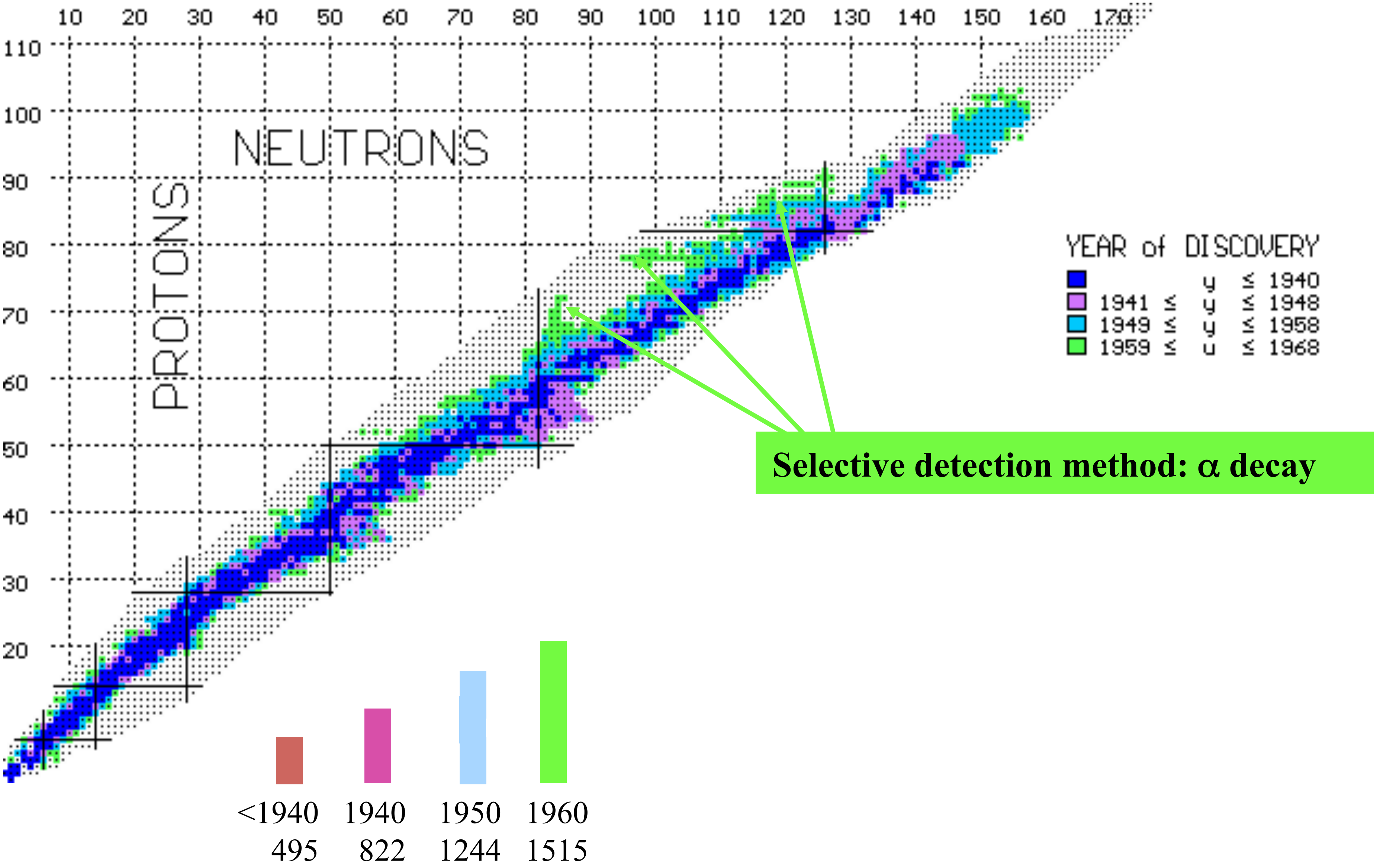
Reactors: n on U

Un po' di Storia…



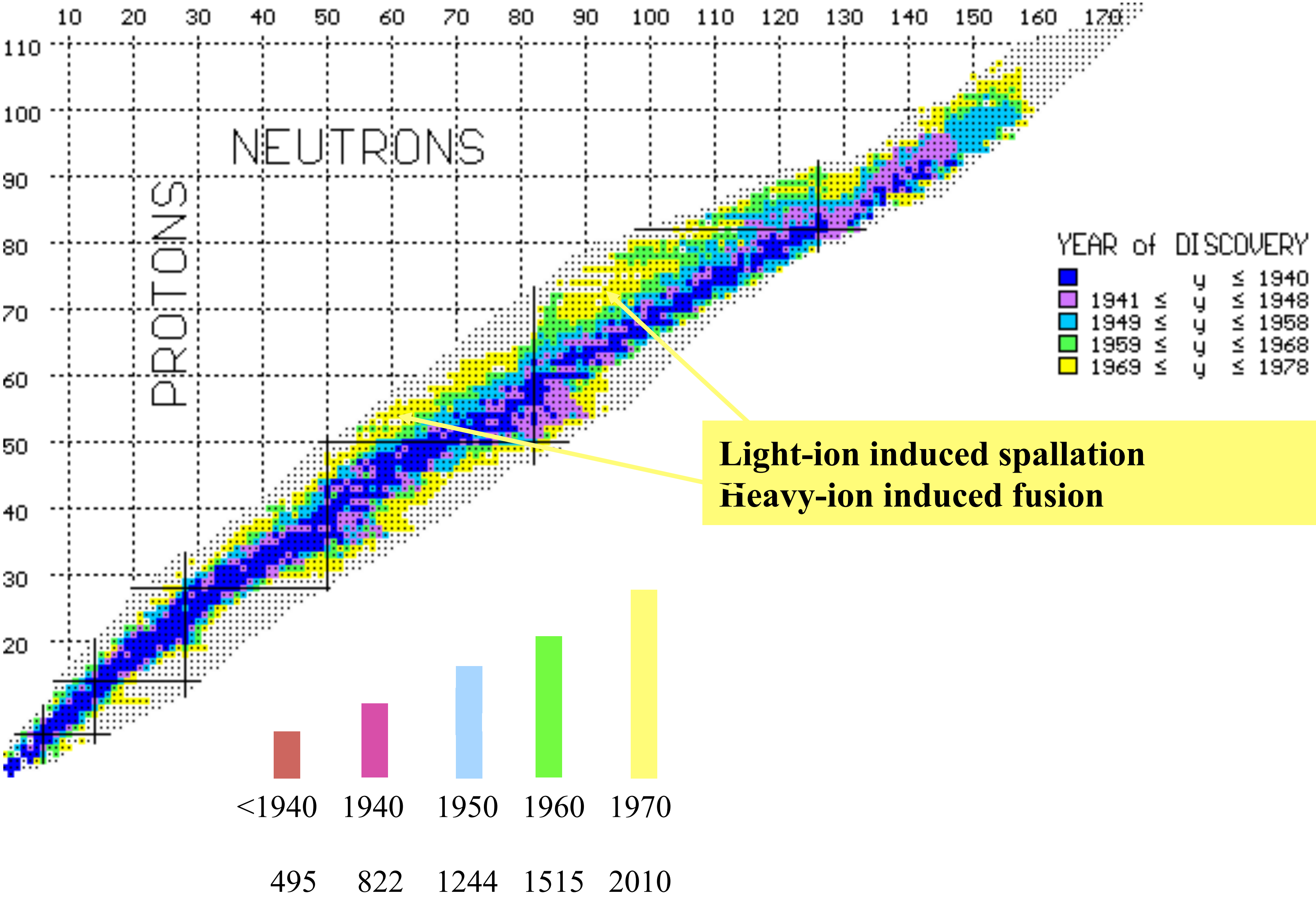
First Isotope Separator experiment
Niels Bohr Institute 1951
fast n on U: Kr and Rb isotopes

Un po' di Storia…



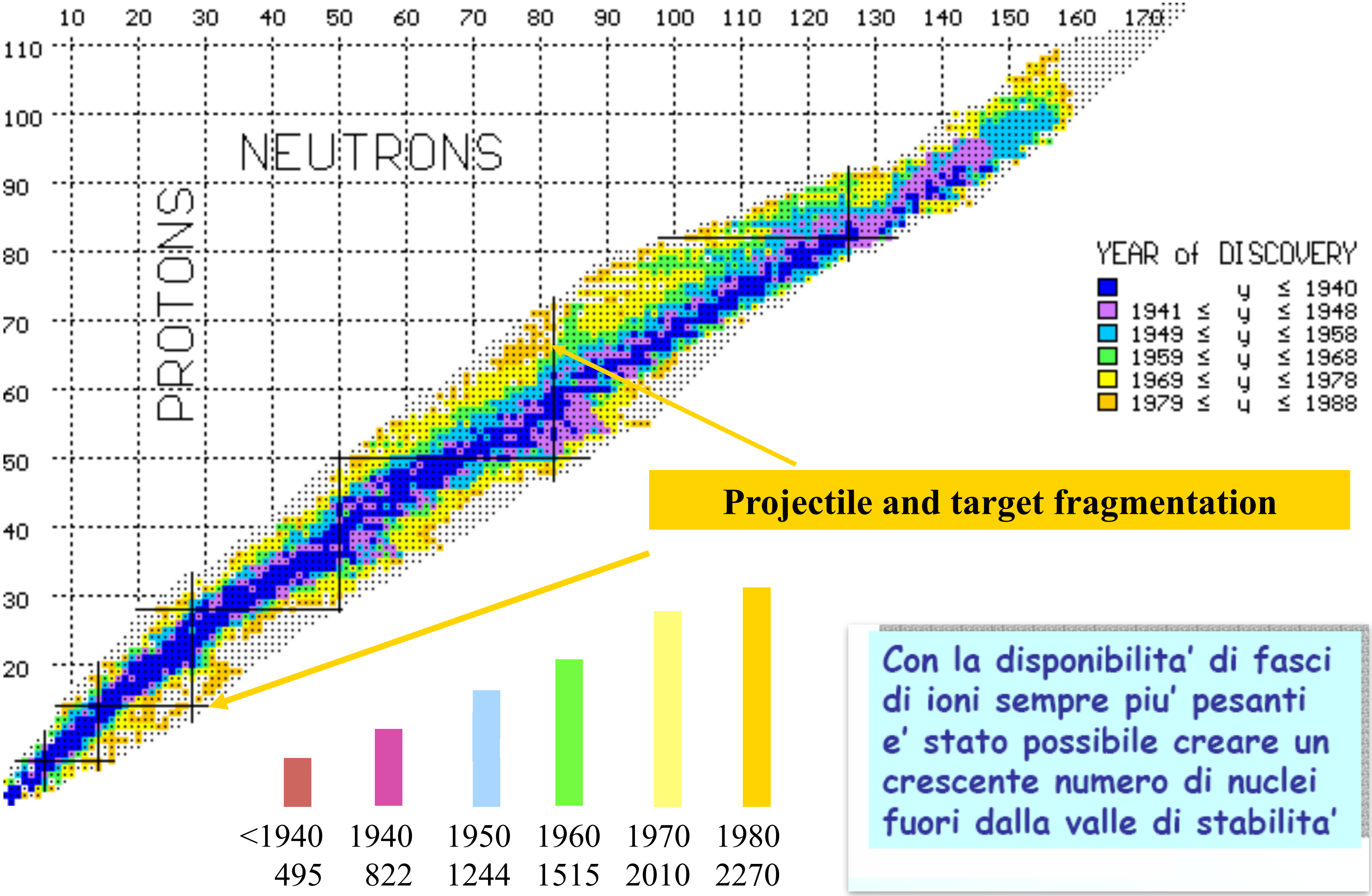
Selective detection method: α decay

Un po' di Storia…



Light-ion induced spallation
Heavy-ion induced fusion

Un po' di Storia…

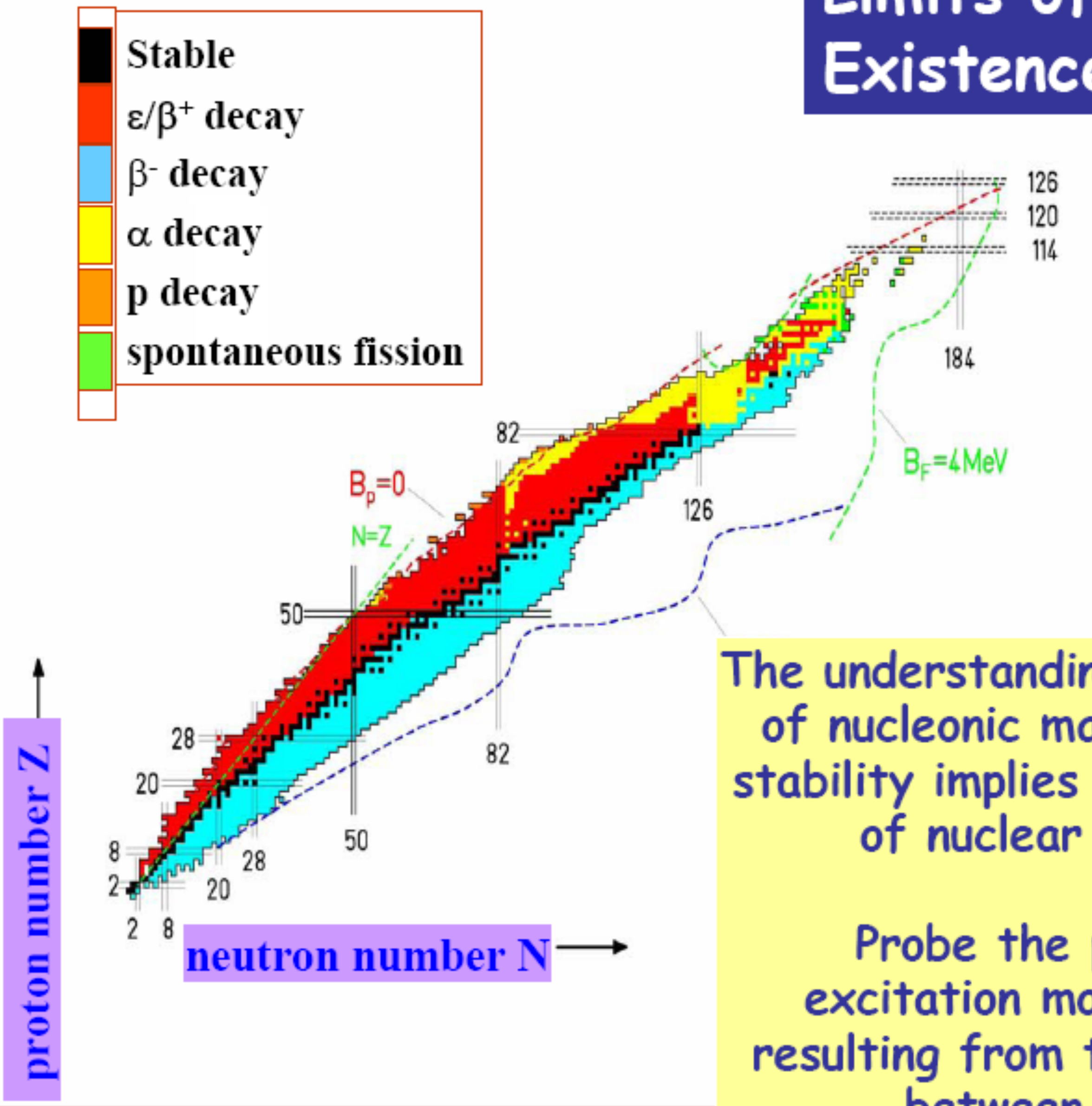


Projectile and target fragmentation

Con la disponibilita' di fasci di ioni sempre piu' pesanti e' stato possibile creare un crescente numero di nuclei fuori dalla valle di stabilita'

TODAY: Around 3000 of the expected 6000 nuclei have been observed

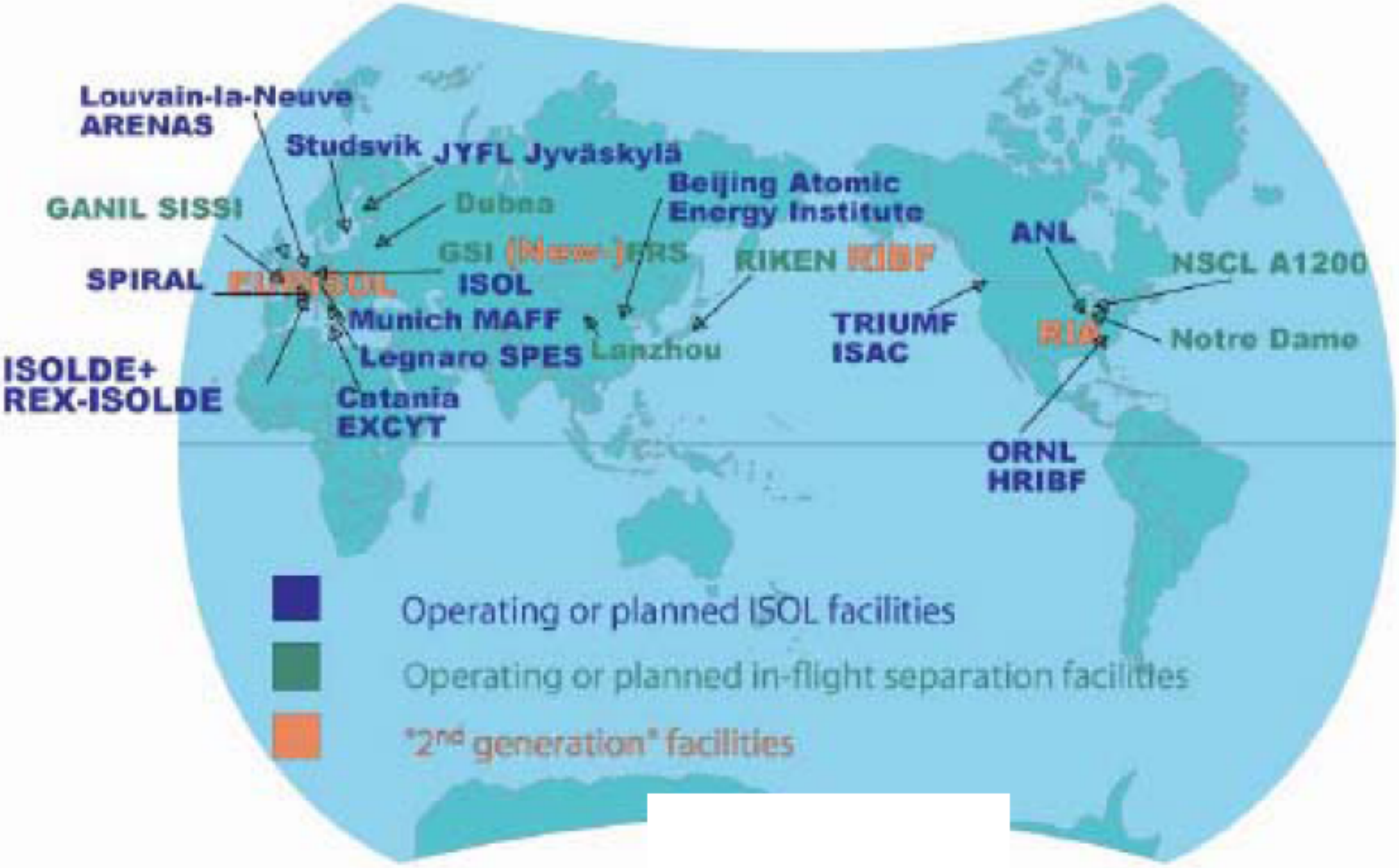
Limits of Nuclear Existence



The understanding of the nature of nucleonic matter far from stability implies the exploration of nuclear structure:

Probe the phases and excitation modes of nuclei resulting from the interactions between nucleons

World Wide Radioactive Beam Facilities



Programma sperimentale vasto che riguarda :

- **Produzione dei nuclei radioattivi**
  - Acceleratori e bersagli di produzione (selezione della regione di A)
    - Masse e altre proprietà dello stato fondamentale
    - (Spin, momenti magnetici, momenti di quadrupolo)
    - Decadimenti (beta e alpha per i nuclei pesanti)

- **reazioni con fasci radioattivi** per studiare le proprieta' di struttura e indagare i vari aspetti e la complessita' del problema a multicorpi

Basse energie (Fino a circa 20 MeV/u)

- Reazioni di trasferimento (proprieta' di particella singola)
- Fusione (proprieta' collettive)
- Eccitazione Coulombiana (Proprieta' collettive)

Alte energie (E> 50 MeV/U)

- Knock out , frammentazione
- eccitazione coulombiana

- **strumentazione** per la spettroscopia associata, particelle cariche, neutroni, gamma e spettrometri di massa e di momento)

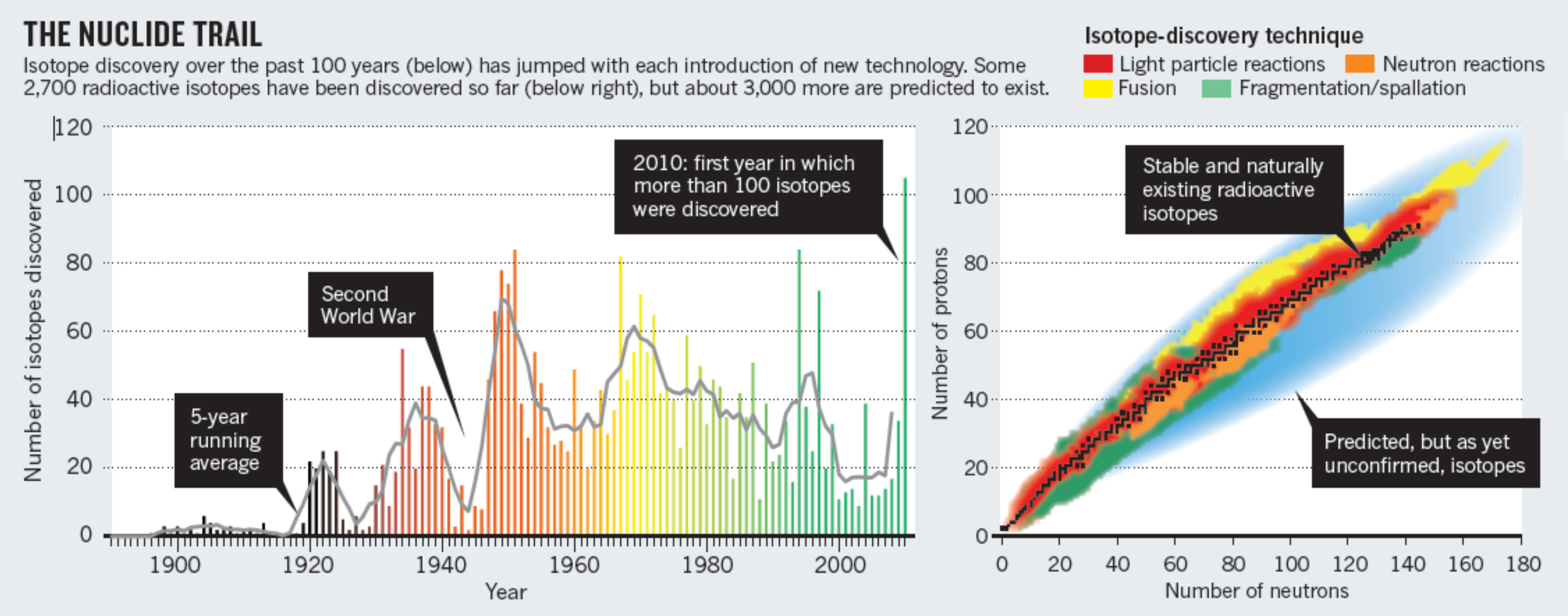
Hans Geiger (left) and Ernest Rutherford's experimental work revealed the nucleus at the centre of atoms.

Comment to Nature,
by M. Thoenessen and B. Sherrill
5 MAY 2011 | VOL 473 | NATURE | 25

In occasion of Rutherford centennial 2011

From isotopes to the stars

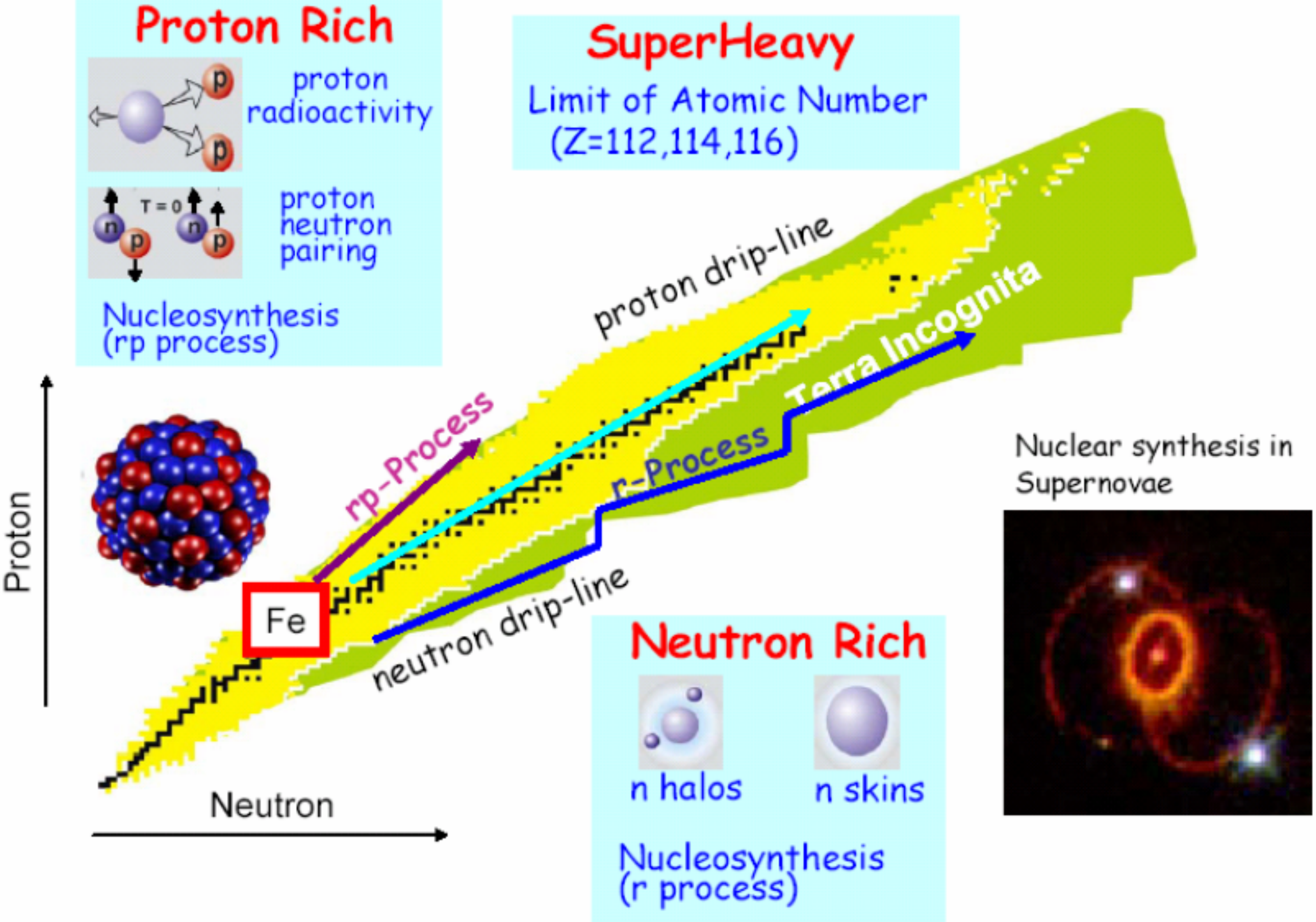
Creating more exotic isotopes will reveal the stellar formation of atoms — a fitting tribute to Ernest Rutherford, say **Michael Thoennessen** and **Bradley Sherrill**.



THE NUCLIDE TRAIL

Isotope discovery over the past 100 years (below) has jumped with each introduction of new technology. Some 2,700 radioactive isotopes have been discovered so far (below right), but about 3,000 more are predicted to exist.

Frontiers of Nuclear Structures: Exotic Nuclei



Proton Rich

proton radioactivity

proton neutron pairing

Nucleosynthesis (rp process)

SuperHeavy

Limit of Atomic Number (Z=112,114,116)

Neutron Rich

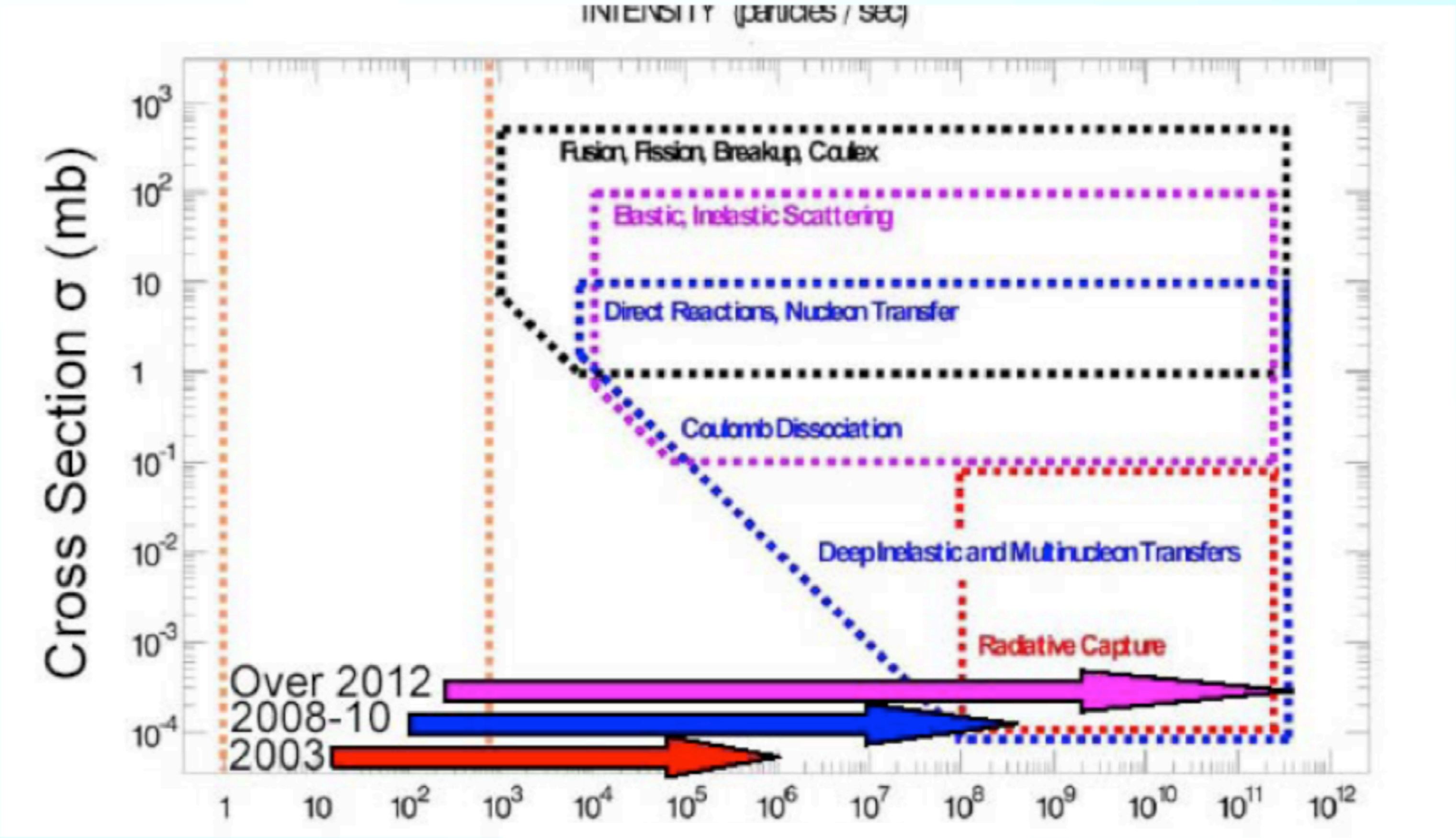
n halos

n skins

Nucleosynthesis (r process)

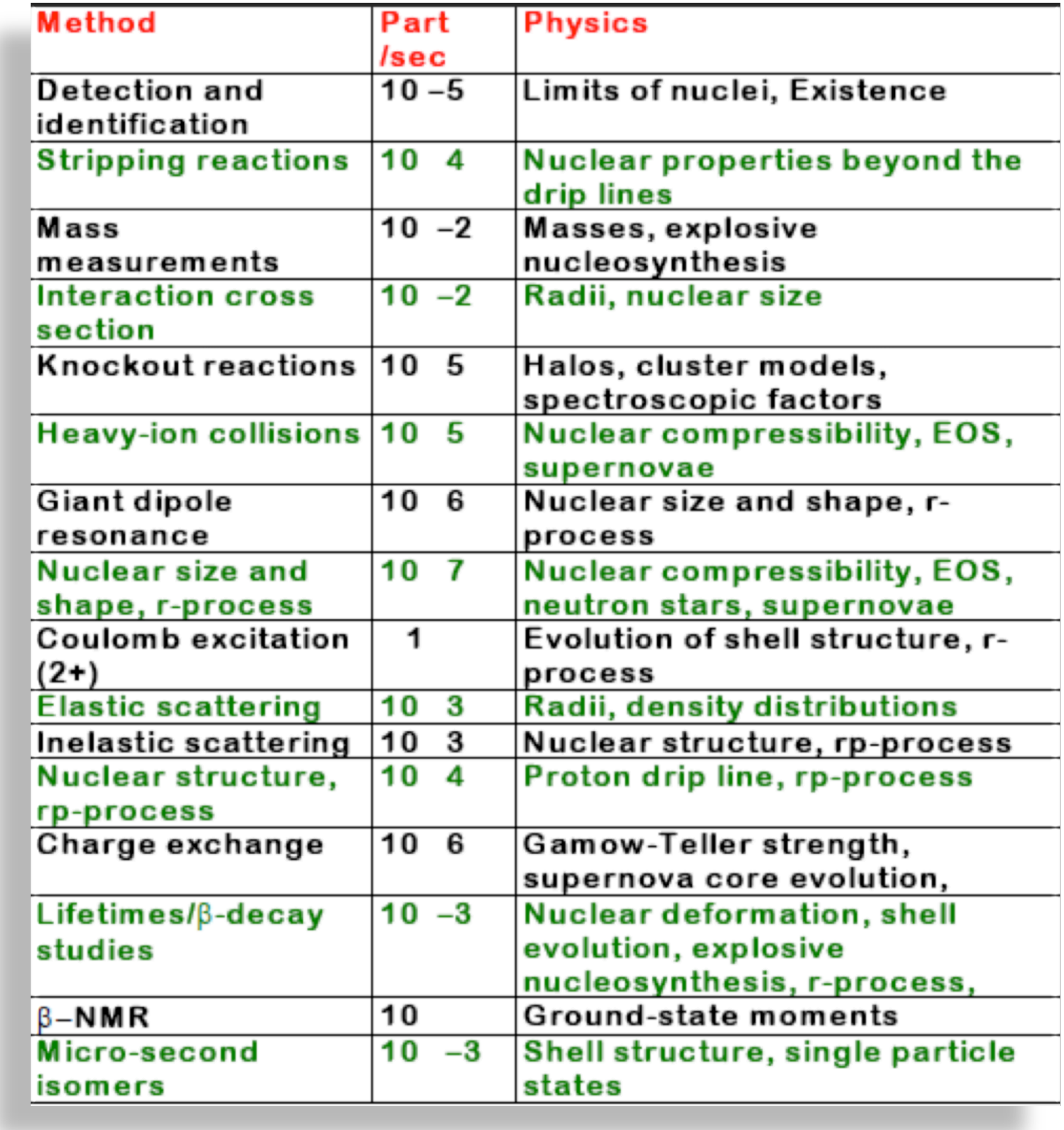
Nuclear synthesis in Supernovae

The different nuclear structure properties (or excitation modes) Needs the use of different reaction mechanisms which correspond to cross sections varying over 8 order of magnitude



Intensity (particle/sec)

Reazioni di Produzione



Method	Part /sec	Physics
Detection and identification	10 –5	Limits of nuclei, Existence
Stripping reactions	10 4	Nuclear properties beyond the drip lines
Mass measurements	10 –2	Masses, explosive nucleosynthesis
Interaction cross section	10 –2	Radii, nuclear size
Knockout reactions	10 5	Halos, cluster models, spectroscopic factors
Heavy-ion collisions	10 5	Nuclear compressibility, EOS, supernovae
Giant dipole resonance	10 6	Nuclear size and shape, r-process
Nuclear size and shape, r-process	10 7	Nuclear compressibility, EOS, neutron stars, supernovae
Coulomb excitation (2+)	1	Evolution of shell structure, r-process
Elastic scattering	10 3	Radii, density distributions
Inelastic scattering	10 3	Nuclear structure, rp-process
Nuclear structure, rp-process	10 4	Proton drip line, rp-process
Charge exchange	10 6	Gamow-Teller strength, supernova core evolution,
Lifetimes/β-decay studies	10 –3	Nuclear deformation, shell evolution, explosive nucleosynthesis, r-process,
β–NMR	10	Ground-state moments
Micro-second isomers	10 –3	Shell structure, single particle states

Primo problema:

Intensita' dei fasci di ioni radioattivi da usare come fasci secondari :

- Quali sono i problemi tecnici per avere fasci con intensita' paragonabili con quella di ioni con nuclei stabili?

(10^{10-11} ioni/s)

- perche' servono alte intensita' ?

$$N_{prod} = N_{inc} \quad N_{targ} \quad \sigma$$

[ions/sec] [ions/sec] [nucl/cm²] [cm²]

$$N_{prod} = \frac{I(eA)}{Z_{proj}\; e\,[coul]} \; \frac{N_A \;\; \chi\,[gr/cm^2]}{A_{targ}\,[gr]} \; \sigma\,[cm^2]$$

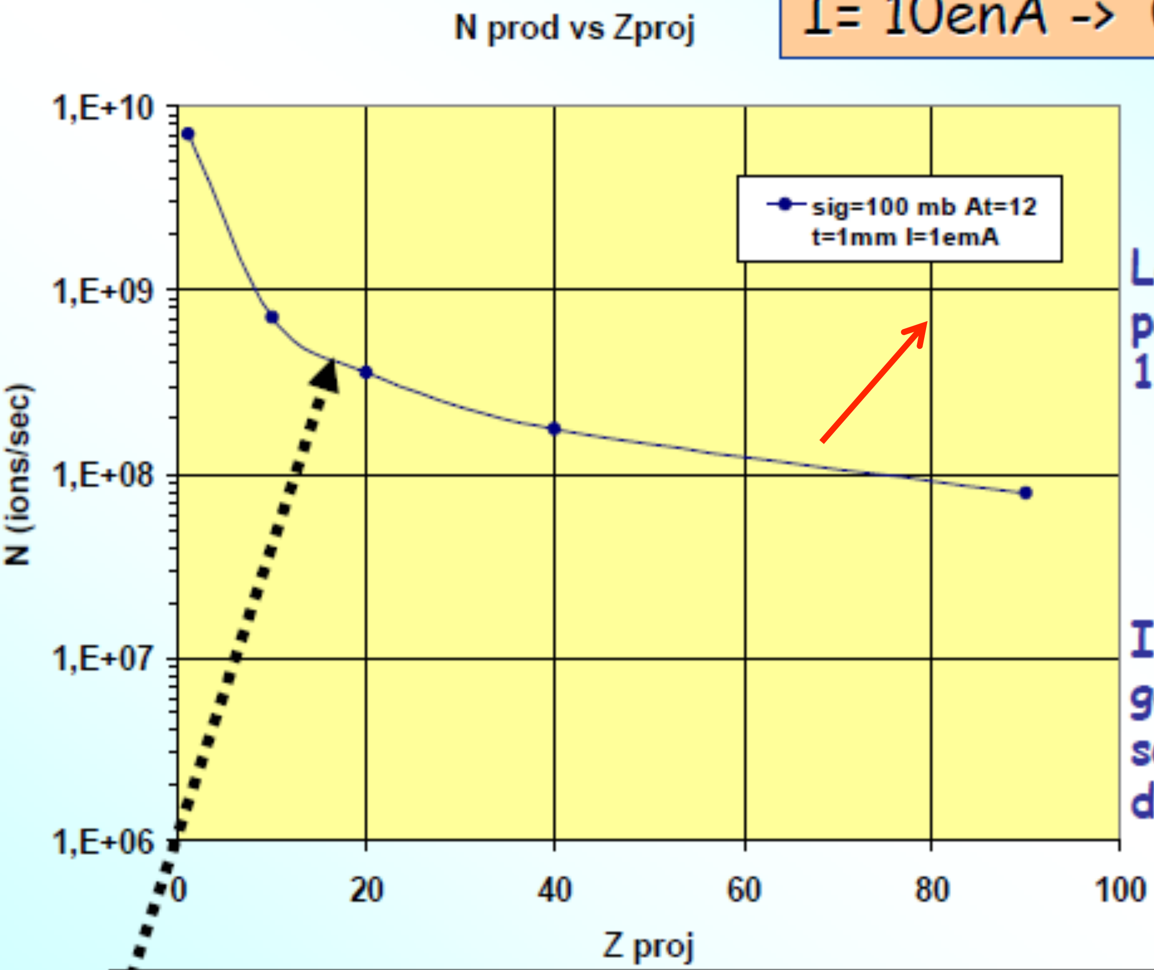
$$N_{prod} = \frac{I(enA)\; 10^{-9}\; 10^{19}}{Z_{proj}\;\; 1.602} \; \frac{6.02\; 10^{23}\; \chi\,[\mu gr/cm^2]\; 10^{-6}}{A_{targ}} \; \sigma\,[mbarn]\; 10^{-27}$$

$$N_{prod} = \frac{3.76\;\; I(enA)\; \chi\,[\mu gr/cm^2]\; \sigma\,[mbarn]}{Z_{proj}\; A_{targ}}$$

$$\chi\,[\mu gr/cm^2] = \rho\,[gr/\,cm^3]\; t[\mu m]\; 10^2$$

Esempio : ρ= 2 gr/ cm³ e t= 1 mm $\chi = 2\; 10^5\; \mu gr/cm^2 = 200\; mg/cm^2$

I= 10enA -> 0.6 10^{11} protons/sec

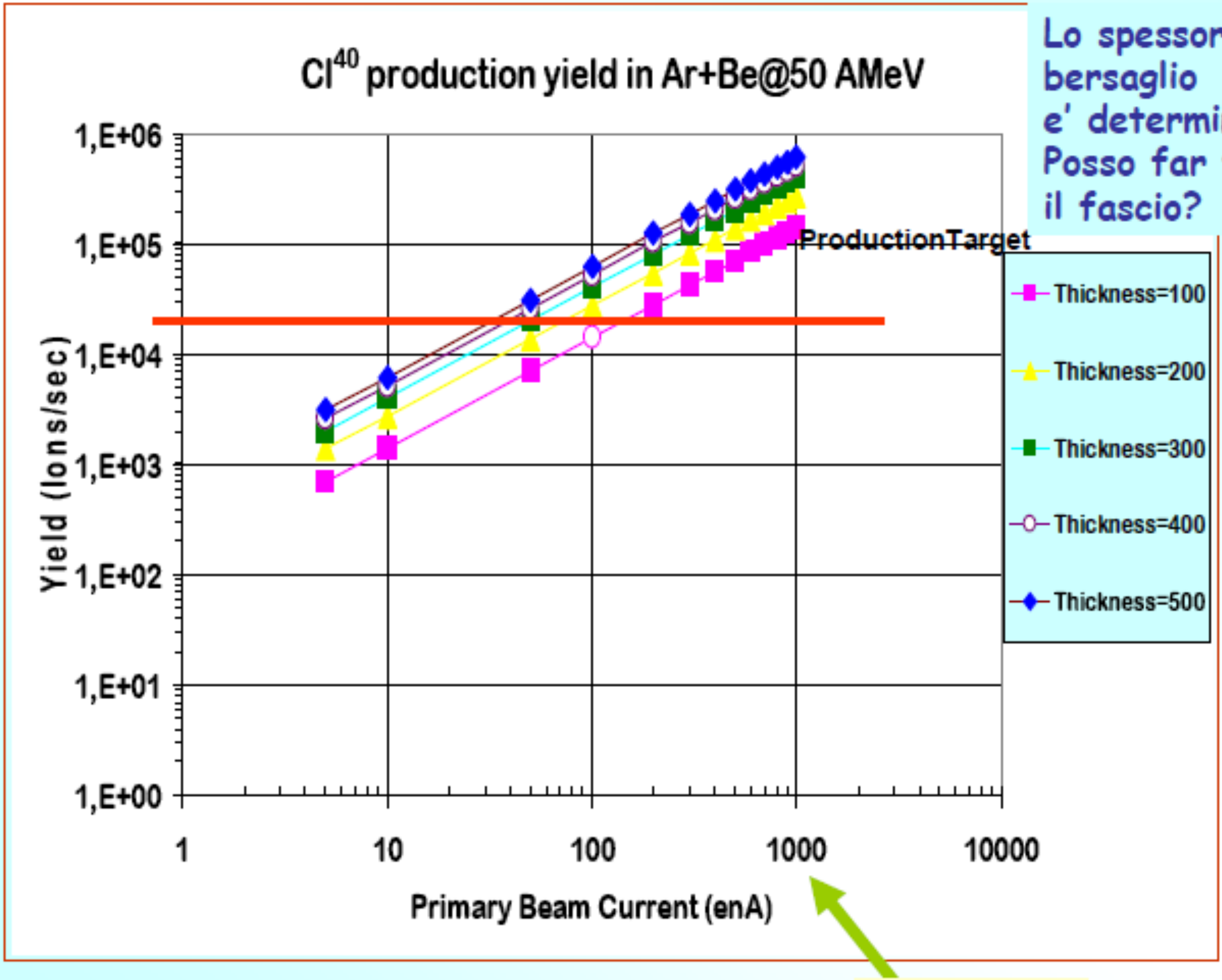


La fisica con i fasci di ioni pesanti si fa con intensita' 10^9-10^{11} ioni al secondo

I fasci secondari di seconda generazione con 10^8 ioni al secondo potenze del'ordine di 100 kWatt!

Potenza (W)= I V = I (Energy/Charge state)

Es: I=1mA E=50 A MeV di O^{16} completamente strippato (O^{8+}) :
P = 1 10^{-3} (50 16/8) 10^6 =100 kW



Lo spessore del bersaglio
e' determinante :
Posso far fermare
il fascio?

≈ 1 kWatt

Fasci radioattivi prodotti utilizzando ioni pesanti

- ➢ Con ioni pesanti, dovuto al breve range non posso fare bersagli spessi se voglio
utilizzare direttamente i prodotti di reazione

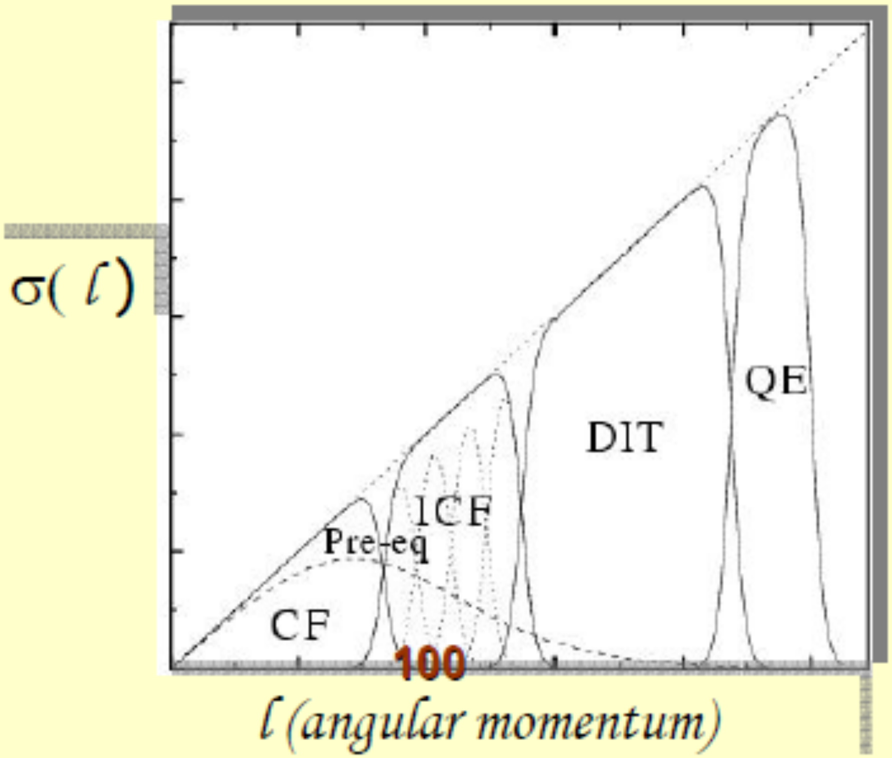
- ➢ Se aumento l'energia in modo da poter fare uscire i prodotti dal bersaglio cambiano
i meccanismi di produzione !

✓Quindi a secondo dei nuclei di interesse devo studiare:

1) quale sono le reazioni migliore per produrli (tipo ed energie)

2) l'energie d'interesse alle quali voglio avere i nuclei radioattivi per studiarne le loro caratteristiche eccitandoli con reazioni nucleari

Reazioni di Produzione

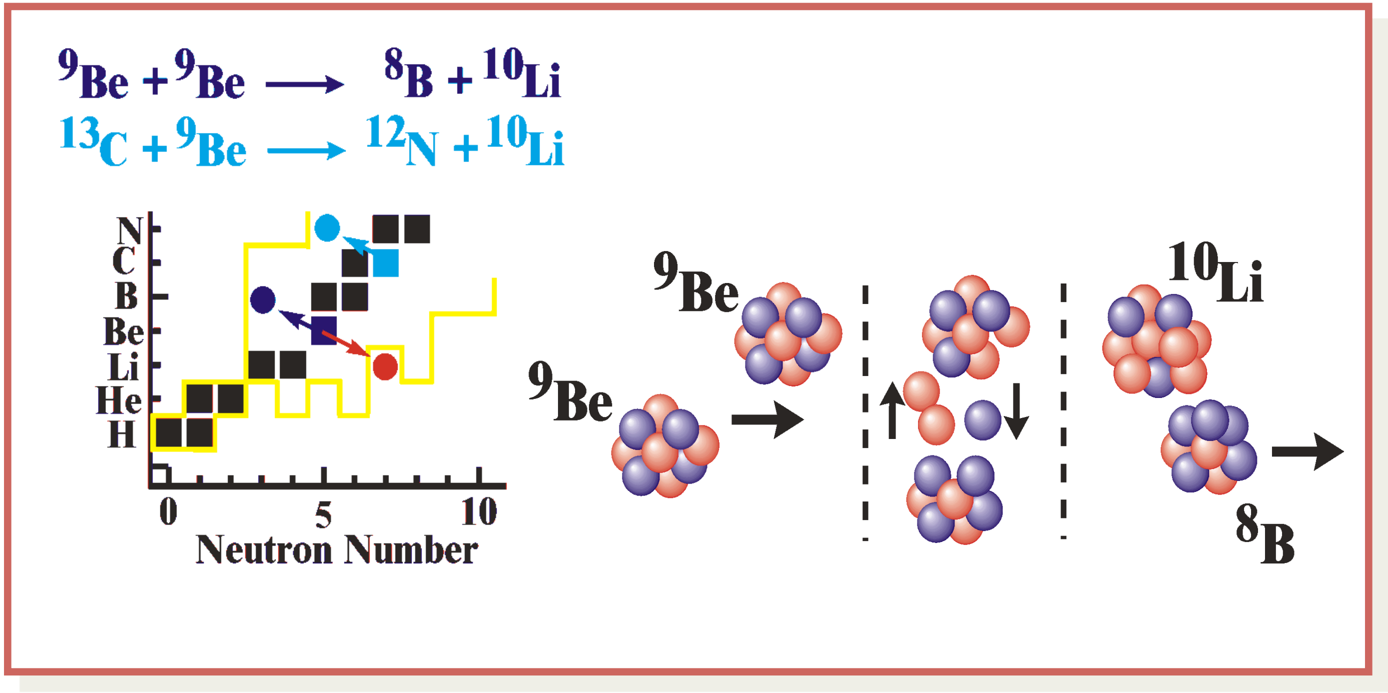


- **Bassa Energia** (Fusione, Fissione, Reazioni dirette , Deep Inelastic)
- **Alta Energia** (Frammentazione Proiettile o Targhetta, Spallation, Fissione in volo)

- peripheral elastic and quasi-elastic (QE) collisions
- semi-peripheral deep-inelastic collisions (DIT) collisions
- incomplete (ICF) and complete (CF) fusion in central collisions
- pre-equilibrium emision typically preceding ICF/CF and DIT

Reazioni di Produzione

Transfer



$$^{9}\mathrm{Be} + {}^{9}\mathrm{Be} \longrightarrow {}^{8}\mathrm{B} + {}^{10}\mathrm{Li}$$

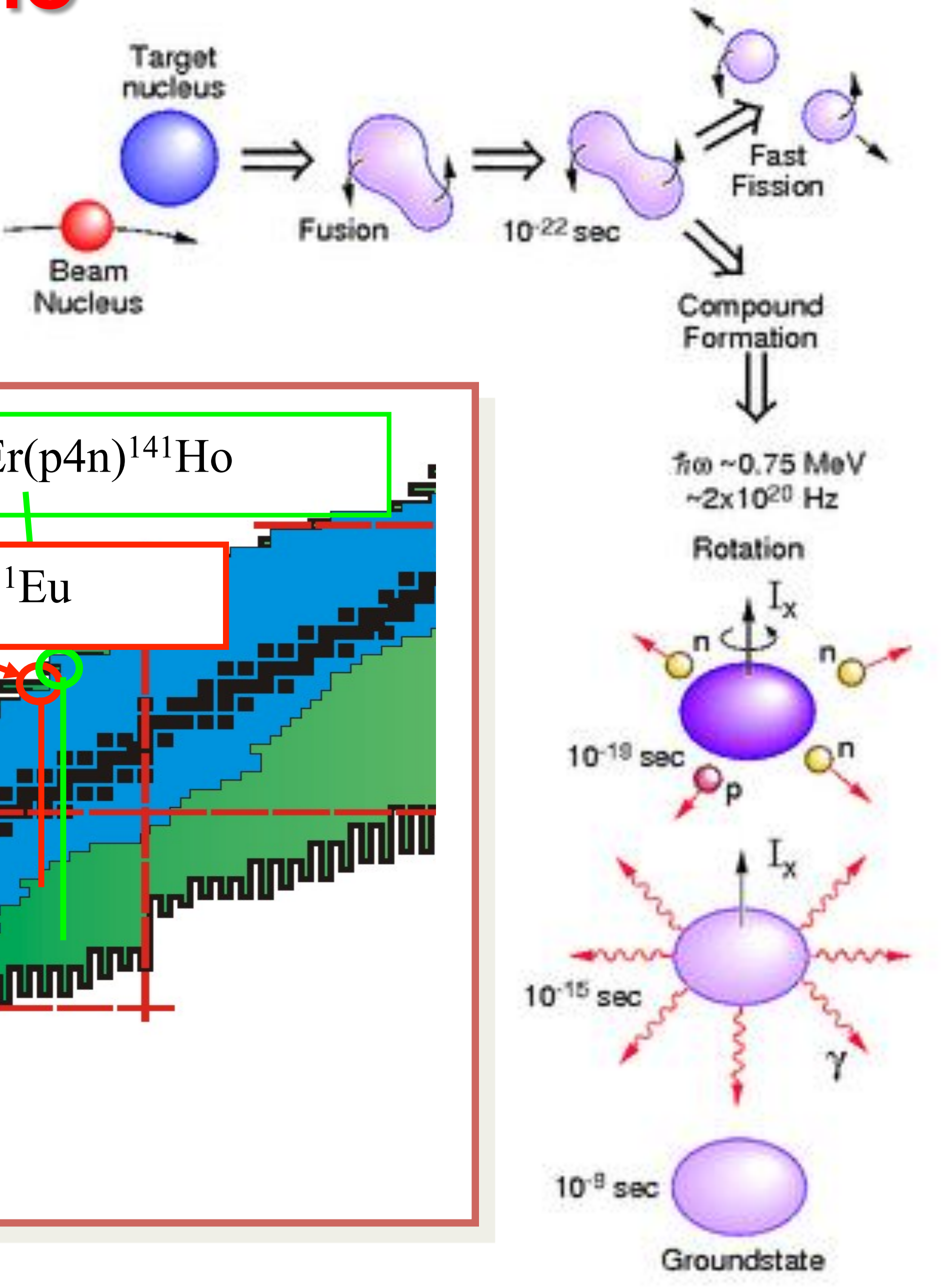
$$^{13}\mathrm{C} + {}^{9}\mathrm{Be} \longrightarrow {}^{12}\mathrm{N} + {}^{10}\mathrm{Li}$$

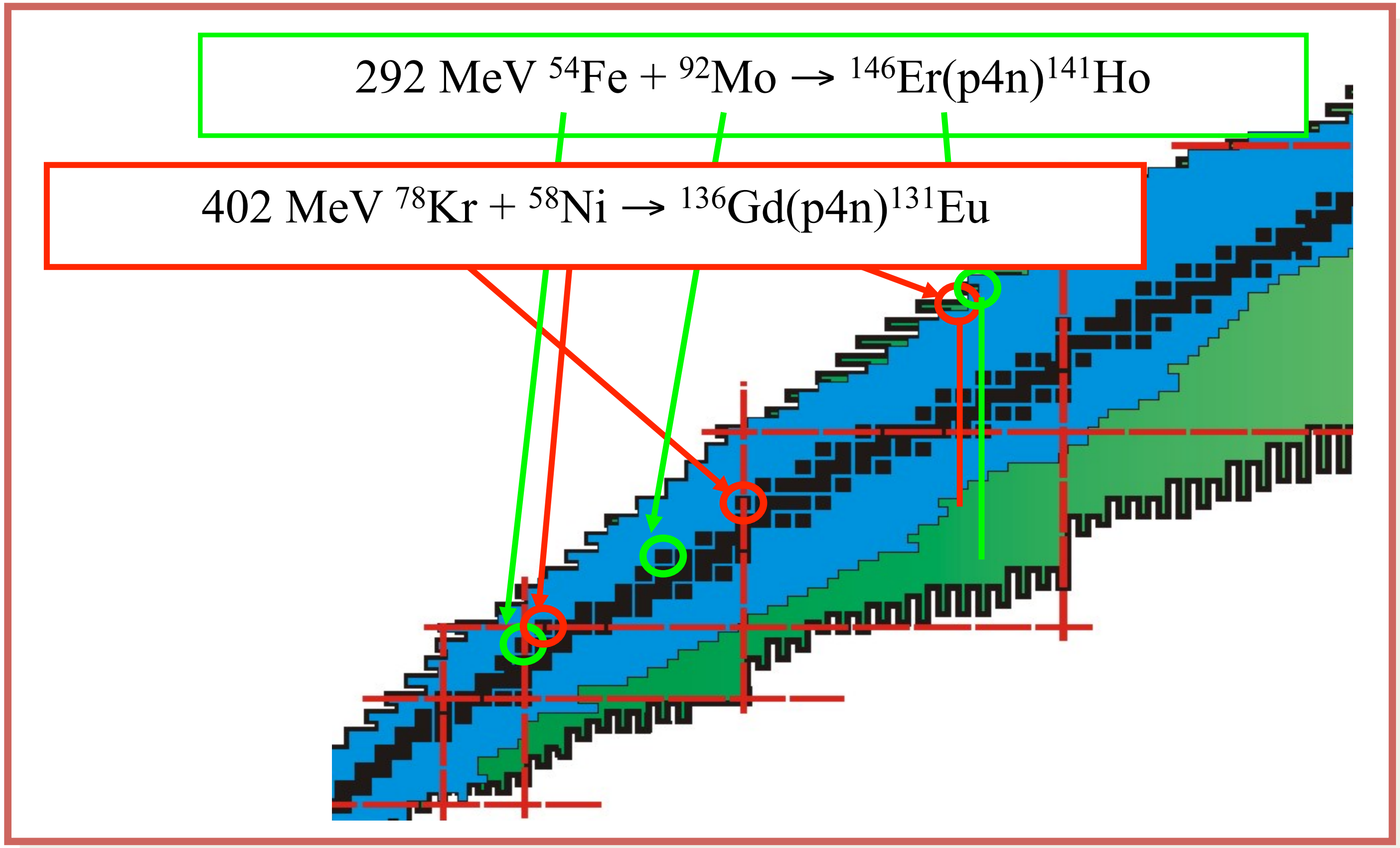
In generale:

- Piccate ad angoli in avanti
- $\sigma \cong 10^{-1}$ – 10 mbarn
- few-nucleons away from projectile and target

Reazioni di Produzione

Fusion





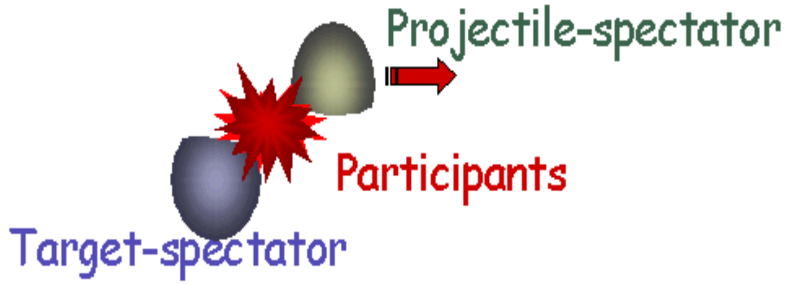
292 MeV ^{54}Fe + ^{92}Mo → ^{146}Er(p4n)^{141}Ho

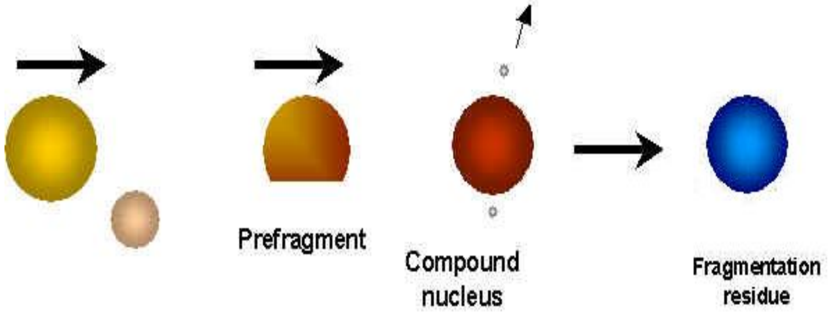
402 MeV ^{78}Kr + ^{58}Ni → ^{136}Gd(p4n)^{131}Eu

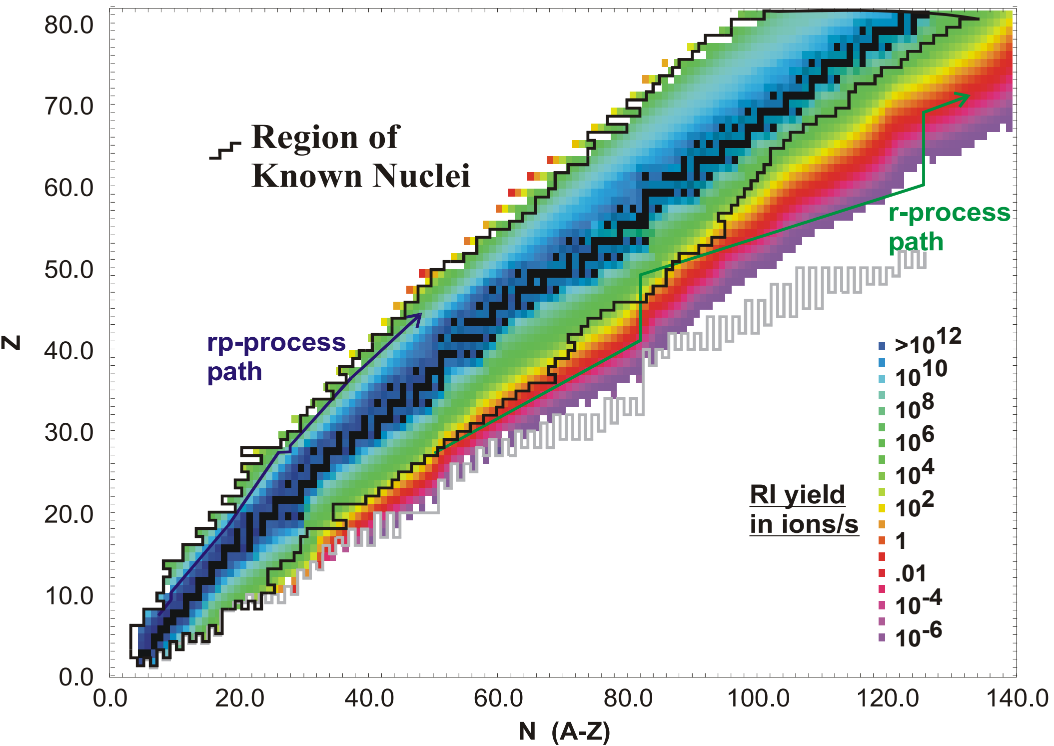
A.A. Sonzogni *et al.,* Phys. Rev. Lett. **83** 1116 (1999)
D. Seweryniak *et al.,* Phys. Rev. Lett. **86** 1458 (2001)

Reazioni di Produzione
Projectile Fragmentation

Participant-spectator reactions at relativistic energies
(above 100 AMeV)



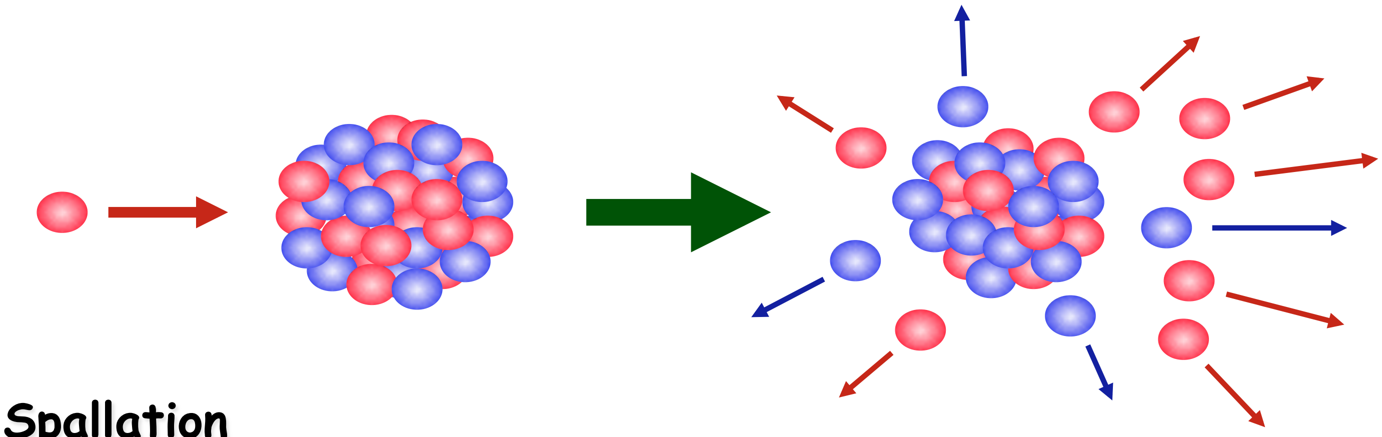




Reazioni di Produzione

Target Fragmentation

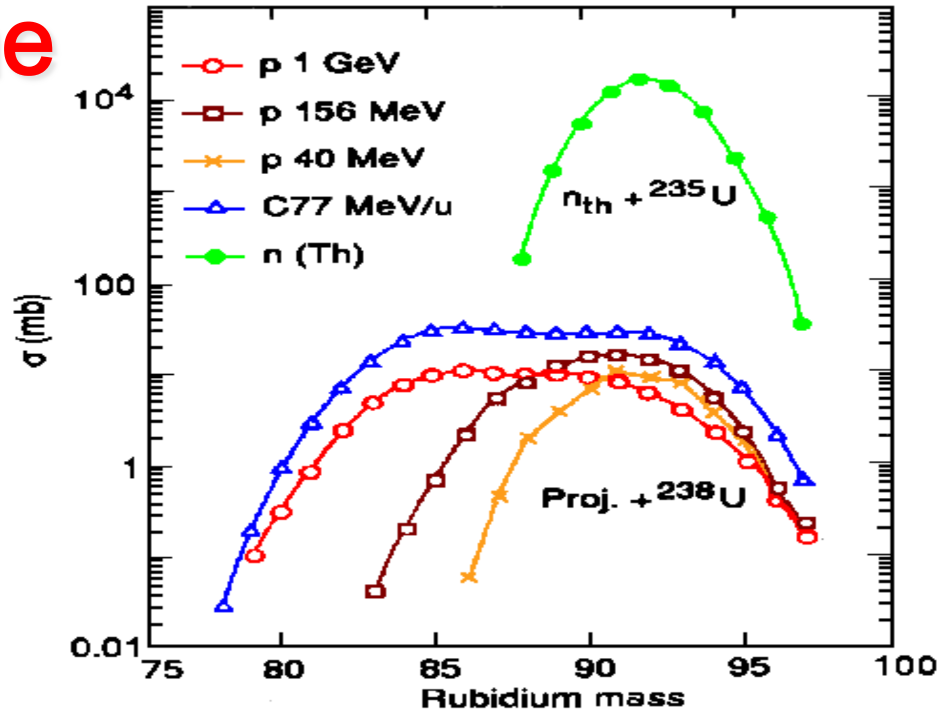
Random removal of protons and neutrons from heavy target nuclei by energetic light projectiles (pre-equilibrium and equilibrium emissions).

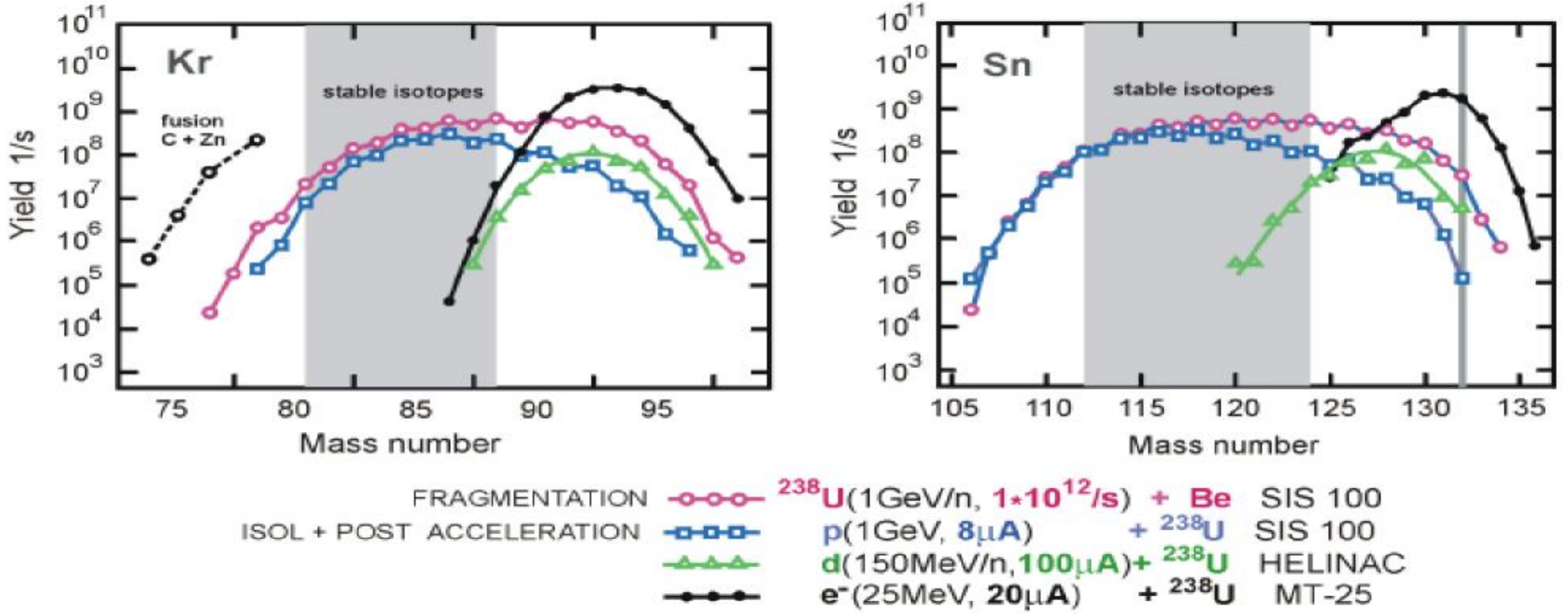


Spallation

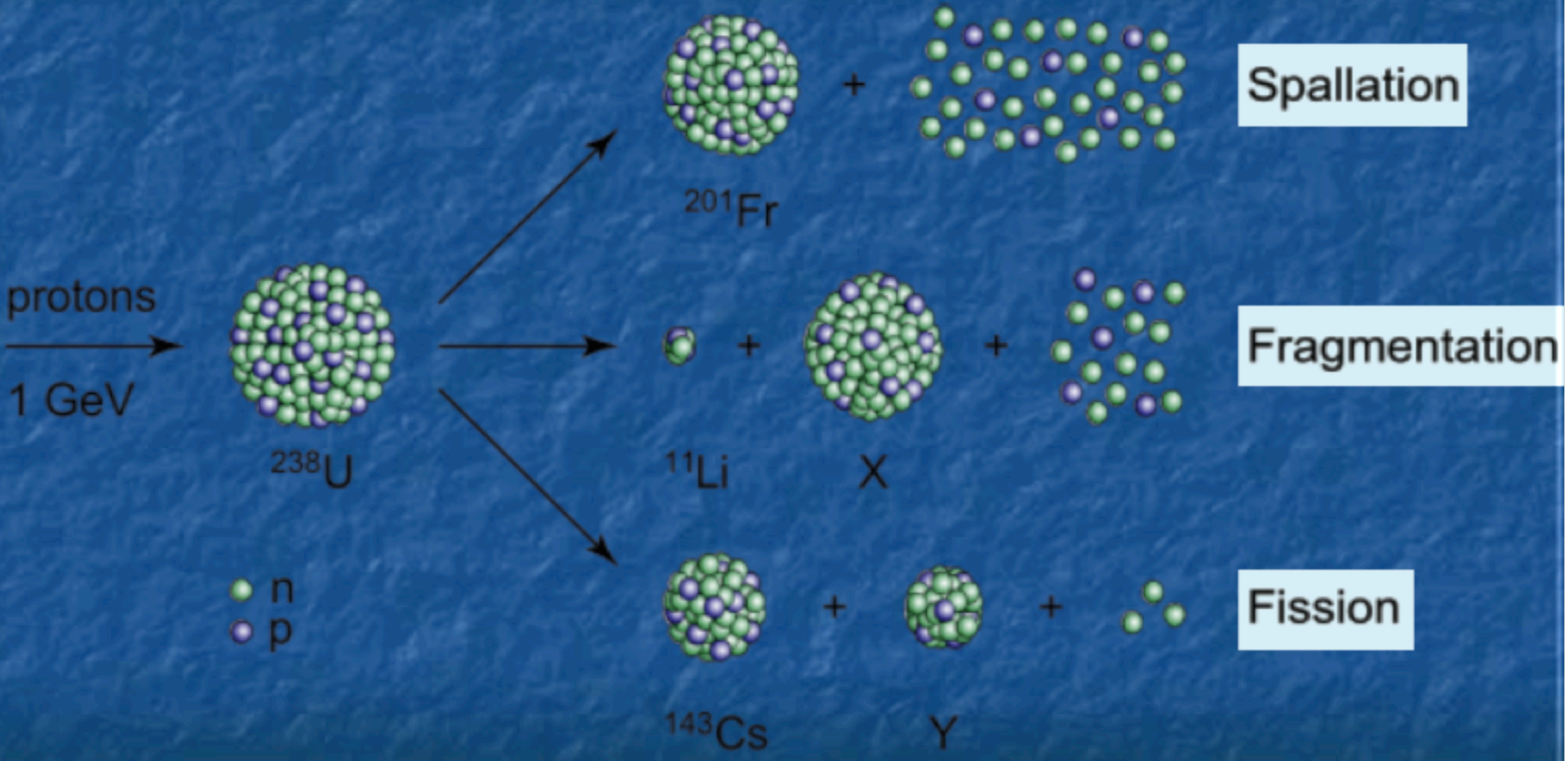
Reazioni di Produzione

Comparisons





Proton induced reactions



protons

1 GeV

^{238}U

^{201}Fr

Spallation

^{11}Li + X +

Fragmentation

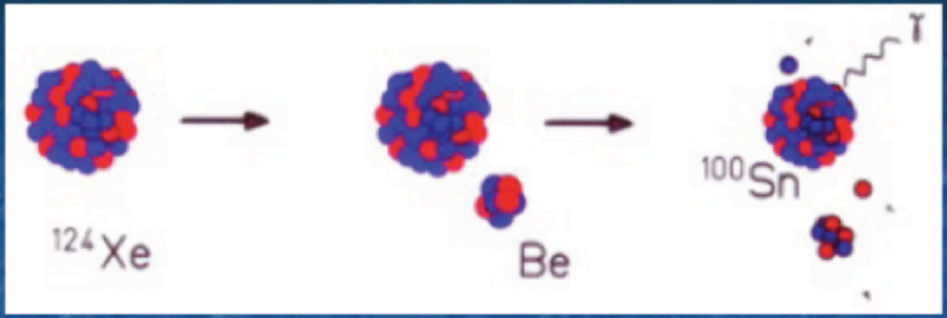
^{143}Cs + Y +

Fission

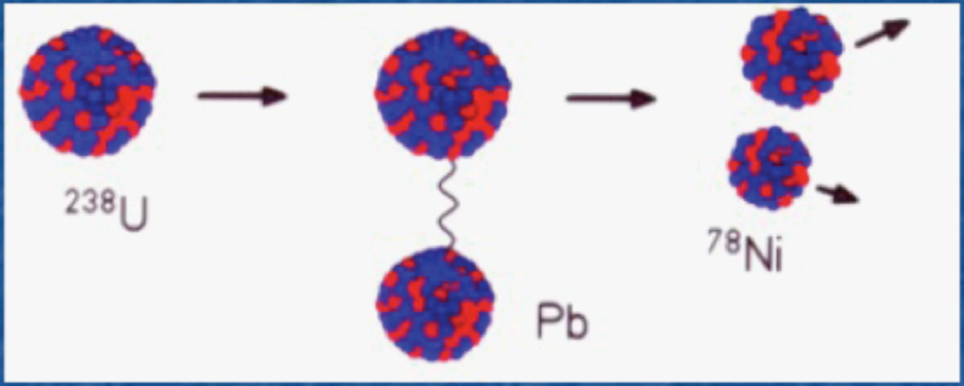
🟢 n

🟣 p

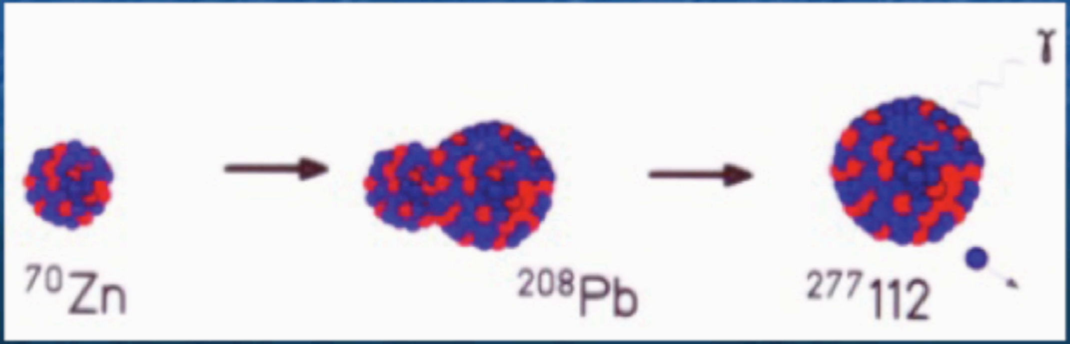
Heavy-ion induced reactions



Fragmentation

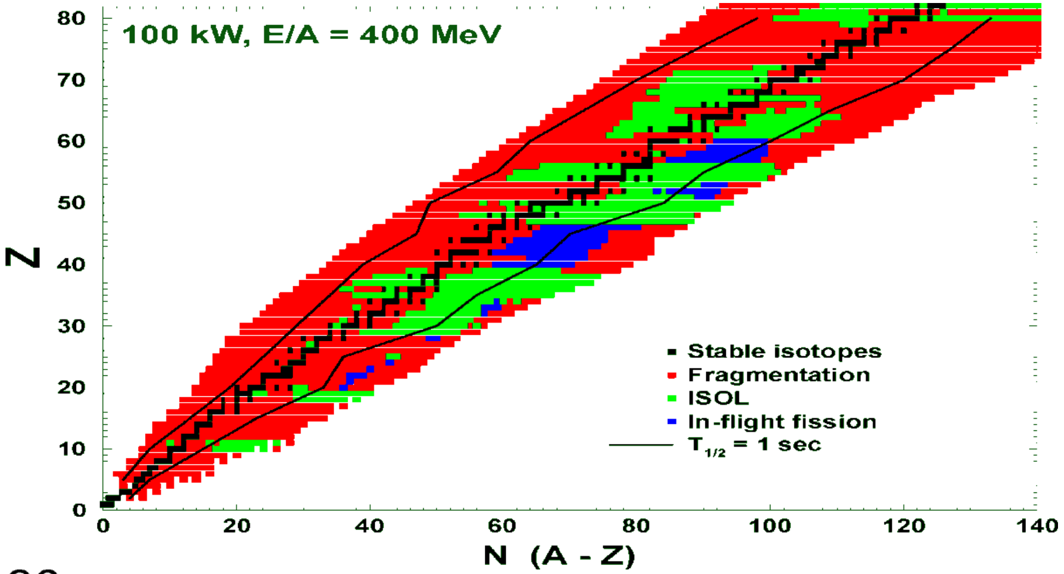


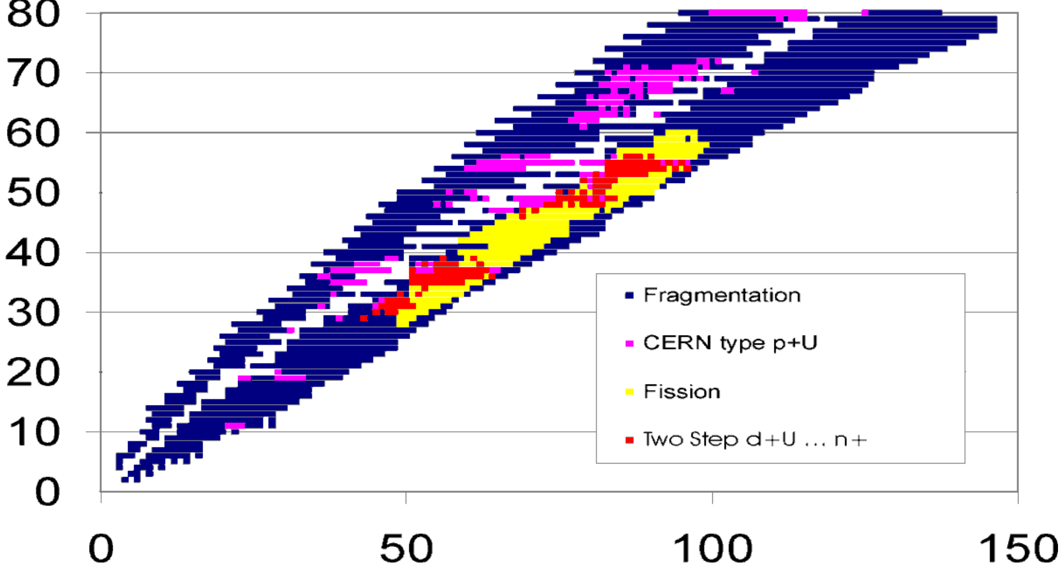
Coulomb dissociation



Fusion

Optimum Reazioni di Produzione





Metodi di produzione

ISOL

Isotope separation on line
fascio primario p, n, d, …ioni pesanti di massa intermedia (energie da 10 di MeV fino a GeV)

In flight

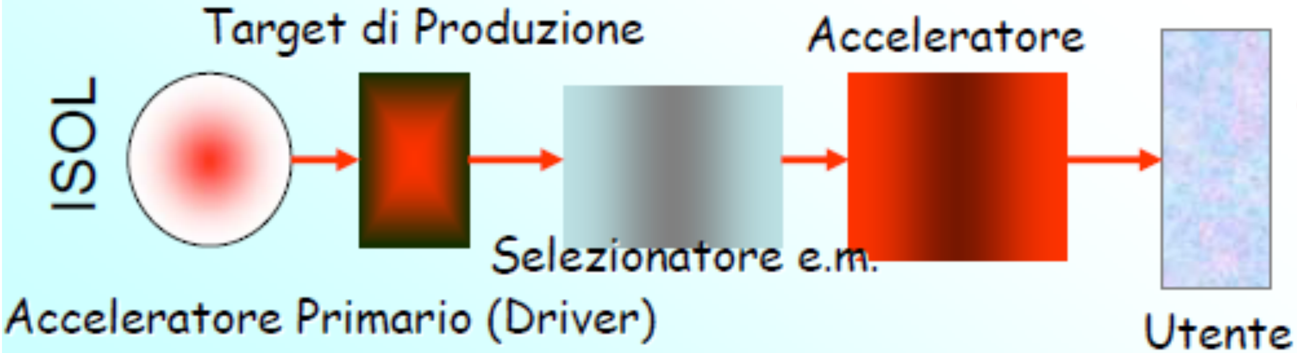
Ioni pesanti (medio pesanti – pesanti)
con energie da circa 100 MeV

Metodi di Produzione

- In-Flight (Fascio prodotto direttamente nella reazione)

- Degraders
- Tagging

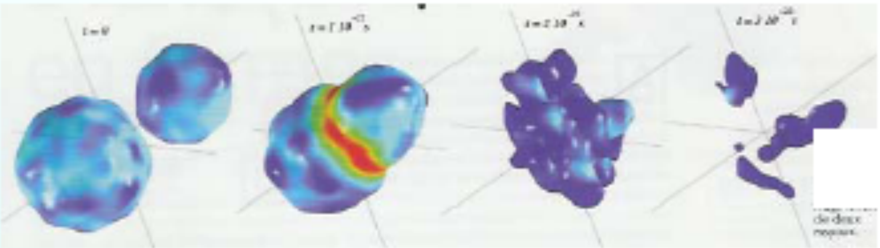
- ISOL (Prodotti di reazione accelerati in un secondo acceleratore)

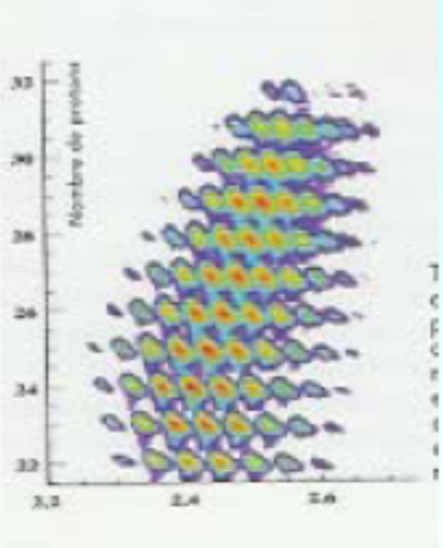


FRAGMENTATION METHOD

Thin target

FRAGMENT SEPARATION

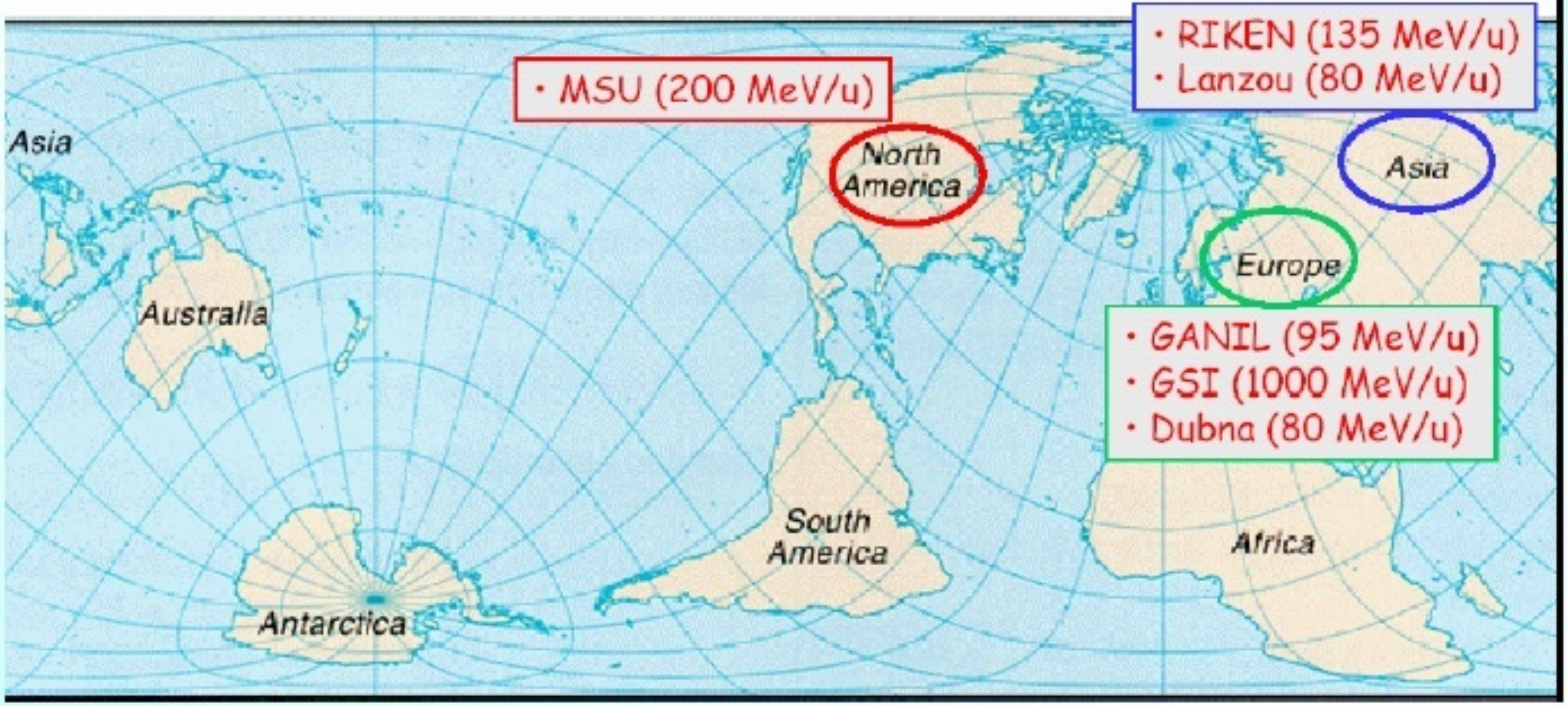




High energy beams
Large spot size and beam cocktails
Exotic Nuclei with short lifetimes < 1ms

Existing facilities:
GSI
GANIL
MSU
RIKEN

In-Flight facilities

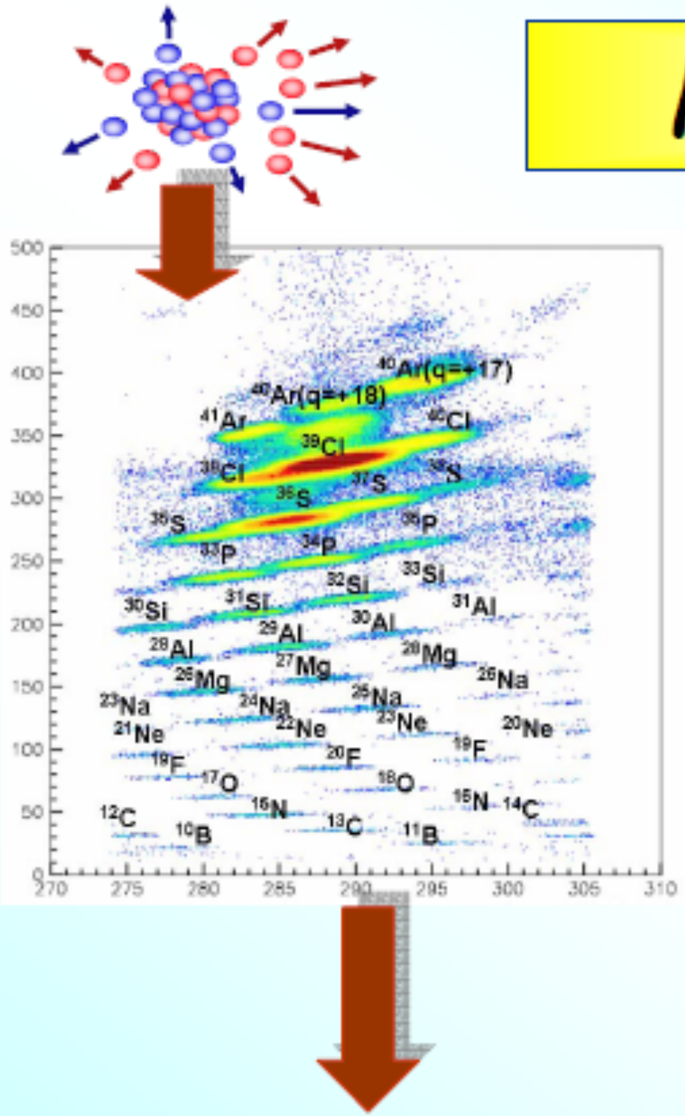


- MSU (200 MeV/u)

- RIKEN (135 MeV/u)
- Lanzou (80 MeV/u)

- GANIL (95 MeV/u)
- GSI (1000 MeV/u)
- Dubna (80 MeV/u)

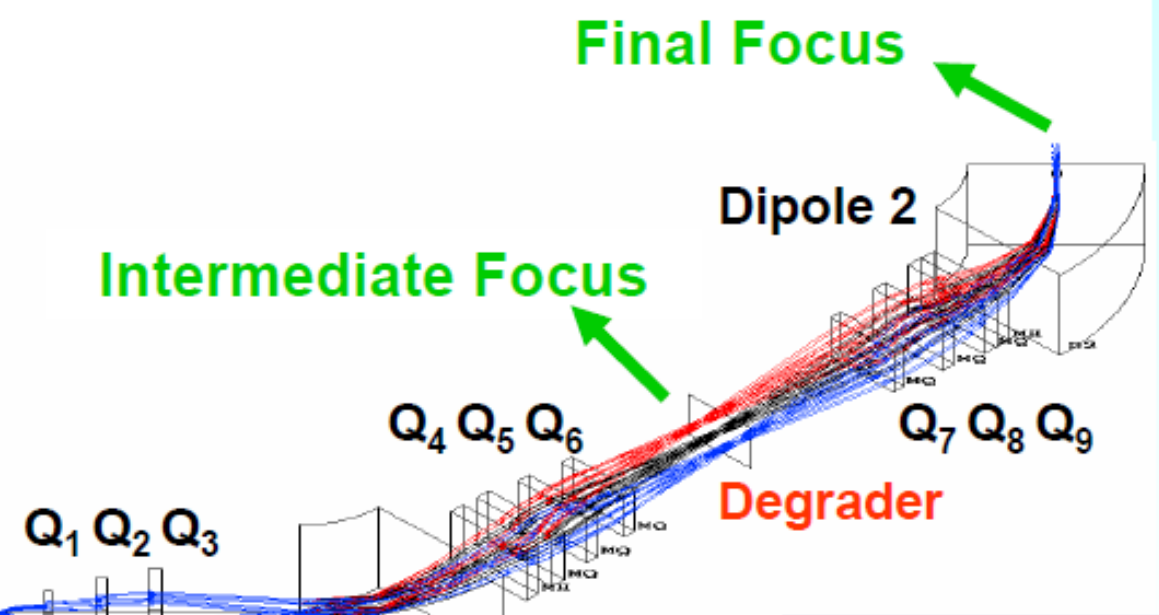
Metodo In-Flight



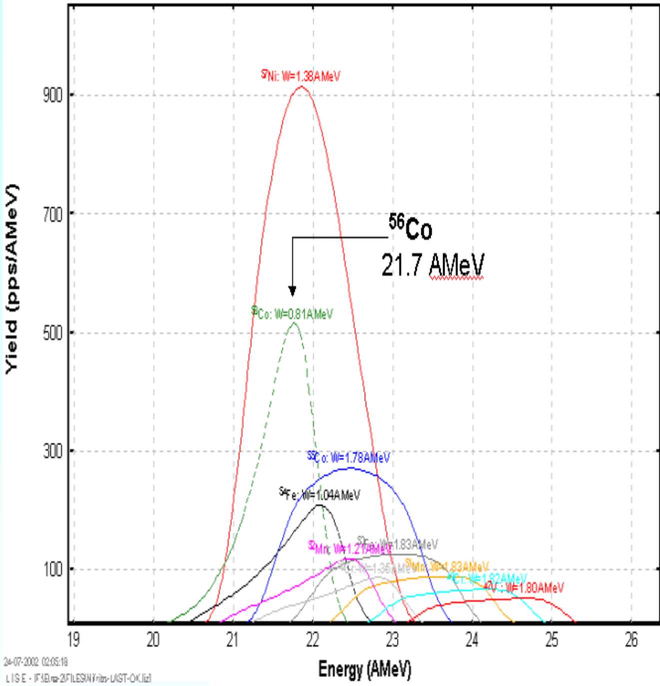
- Relativi problemi di radioattività
- RIBs con vite medie piccole (<msec)

- RIBs non "monoenergetici"
- Energia fascio dopo la frammentazione
  → NON REGOLABILE

- Separazione ElettroMagnetica (Coktail di RIBS)
- Uso di "Degrader"



$$B\rho = \frac{mv}{q} = \frac{p}{q} = \frac{Av}{qc^2}$$



The relative energy loss in the degrader is given by:

$$\frac{dE}{E} \cong eK\frac{A^3}{Z^2}$$

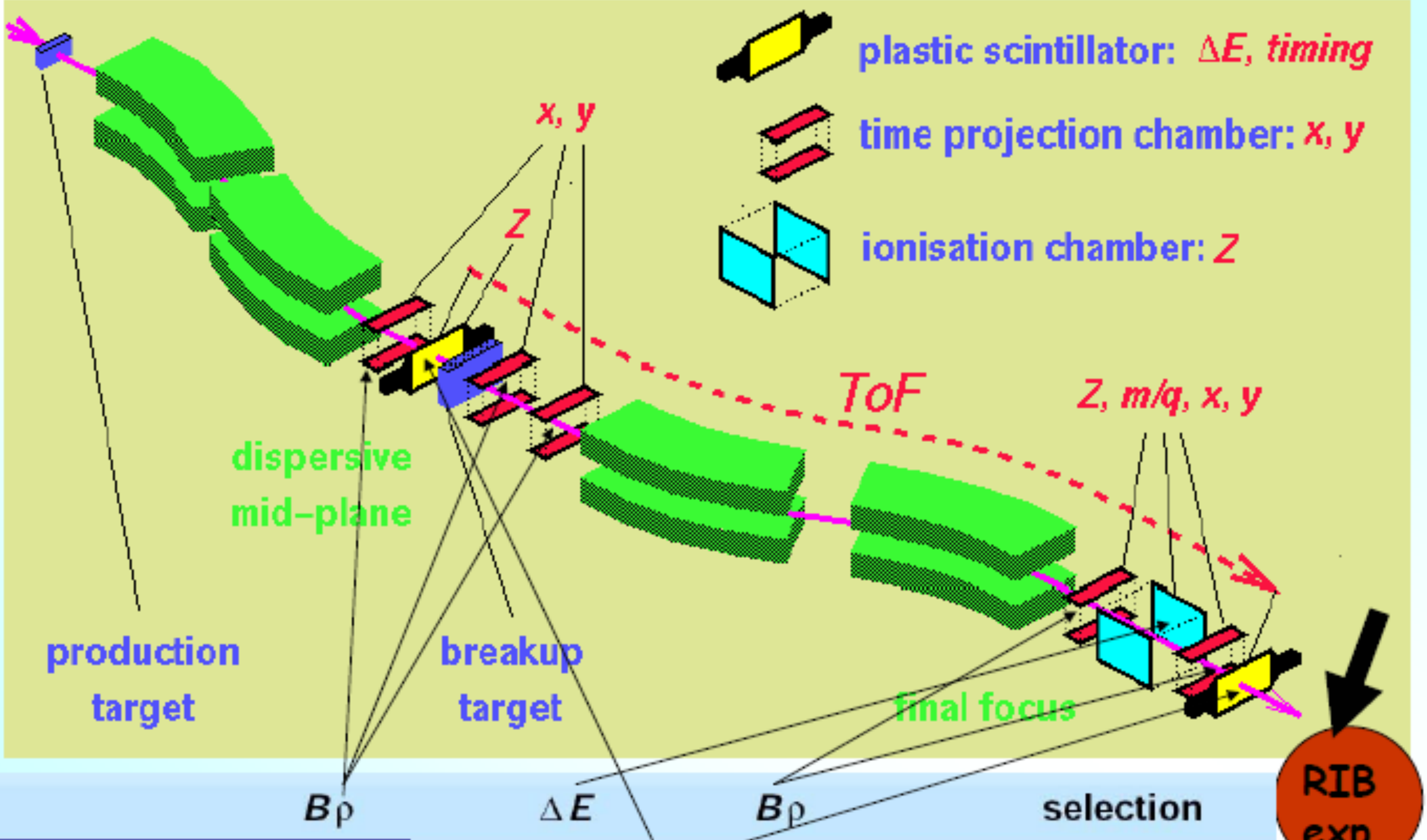
K: constant typical of the degrader
A: nucleus mass
e: thickness of the degrader
Z: atomic number

☹ ENERGY STRAGGLING
☹ ANGULAR STRAGGLING
☹NUCLEAR REACTIONS

INTENSITY LOSS

Thickness and material are chosen as a compromise between desired and undesired effects

FSR@GSI :



Bρ	ΔE	Bρ	selection

ToF Bρ → A/Q

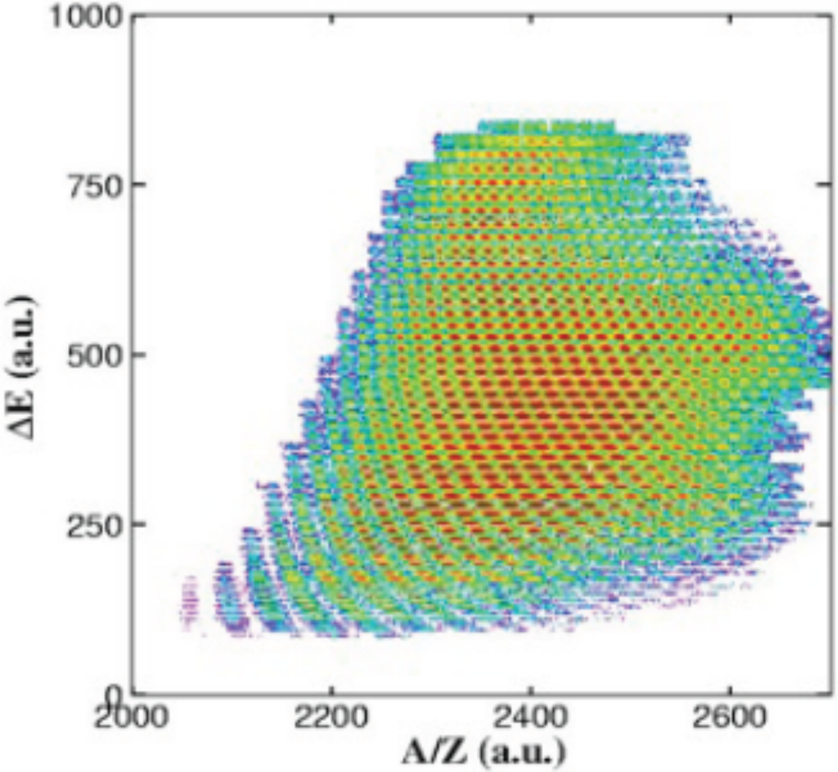
ΔE → Z

} identification

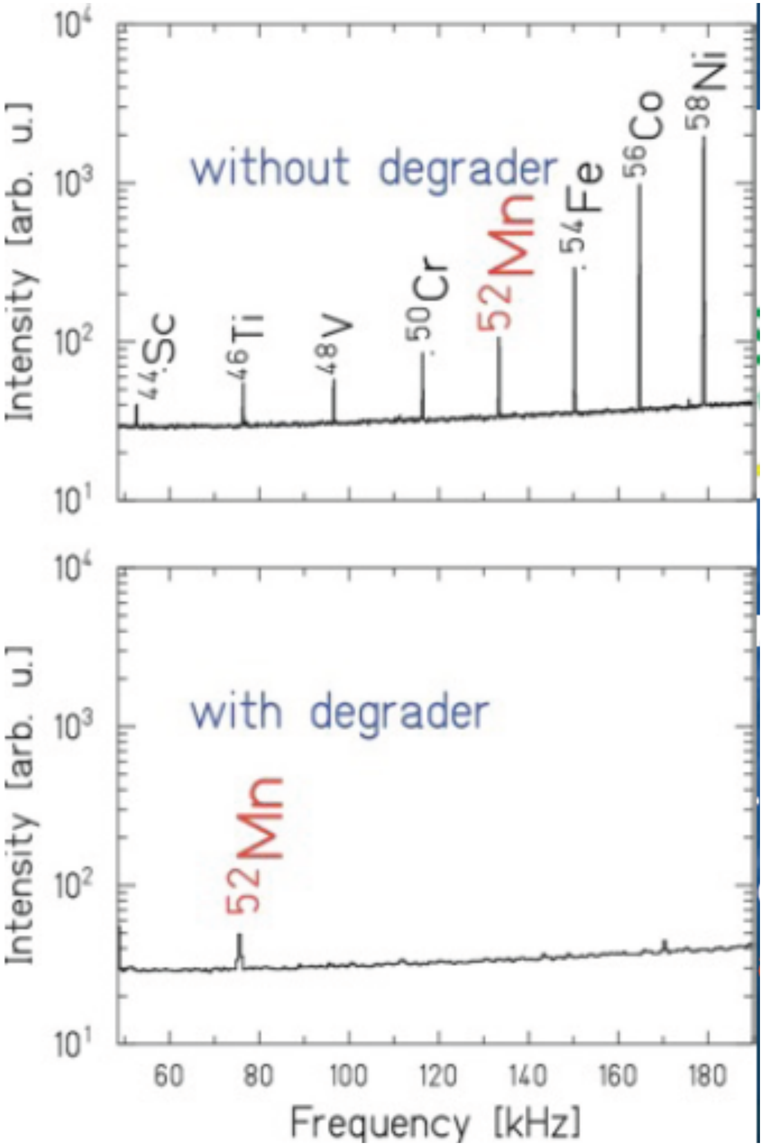
$$B\rho = \frac{mv}{q} = \frac{p}{q} = \frac{A\boxed{v}}{qc^2} \rightarrow \text{ToF}$$

In-Flight production & separation

About 1000 nuclear residues identified



A/Z-resolution ~10^{-3}



FASCI radioattivi a Bassa energia : Perche' servono?

- Reazioni attorno alla barriera (trasferimento, deep-inelastic, fusione) per popolare gli stati eccitati dei nuclei esotici e studiare la loro struttura

- La velocita' del nucleo emettitore ha $\beta<0.2$ e quindi la spettroscopia γ e' piu' facile che con i fasci di Frammentazione on- flight

- **Caratterizzare le eccitazioni dei nuclei con misure ad alta risoluzione:**

Spettroscopia gamma

usare rivelatori piu' segmentati ed efficienti per identificare il punto d'interazione per la correzione Doppler (Progetto AGATA)

ISOL TECHNIQUE

Ion projectiles
stopped
in a thick target
target heated and
the fragments
diffuse

Separation
of the fragments

Post acceleration of the fragments

Ionization of the fragments
Charge breeder

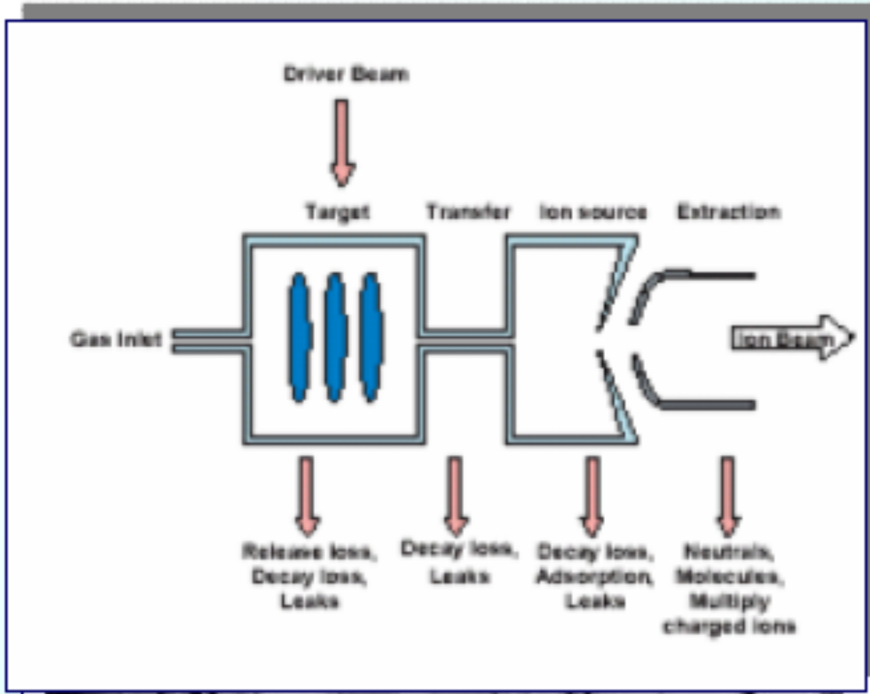
Existing facilities
Oak-Ridge
Triumf
Rex-Isolde
SPIRAL
Excyt

Good beam quality (pure beam and well focussed) – ideal for beams up to 50 MeV/u

Limitation to nuclei with lifetimes larger than 1 ms

Metodo ISOL

sviluppato al
Niels Bohr Institute
negli anni 50



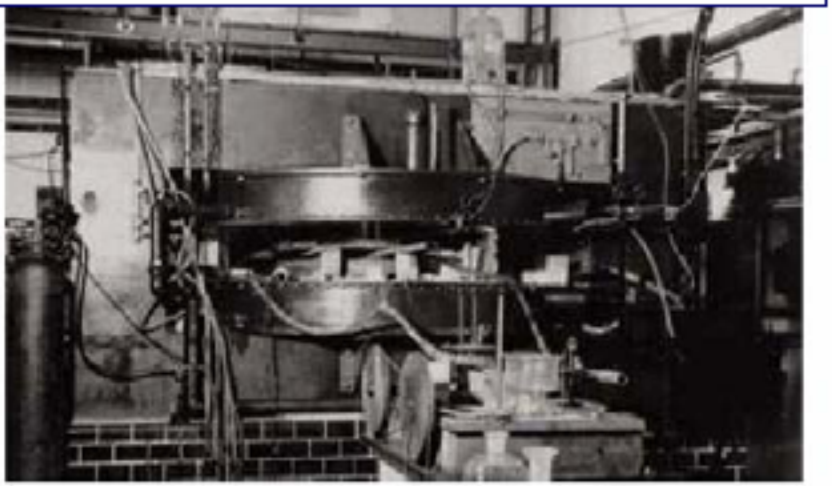
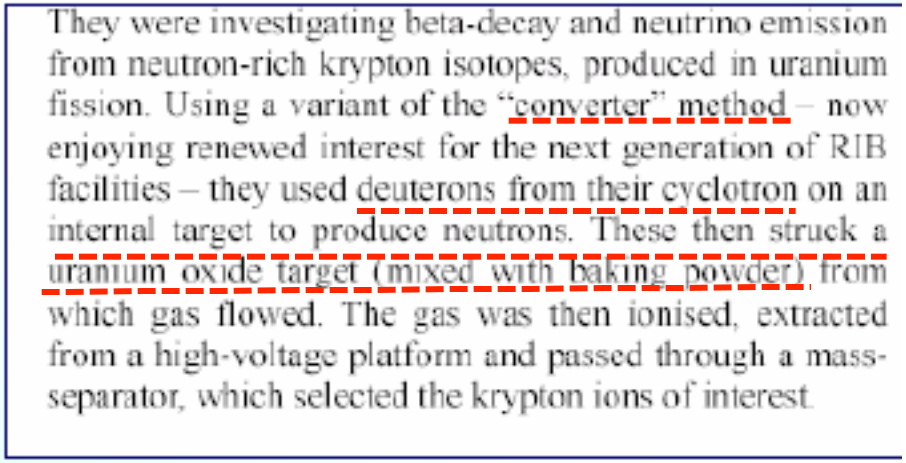
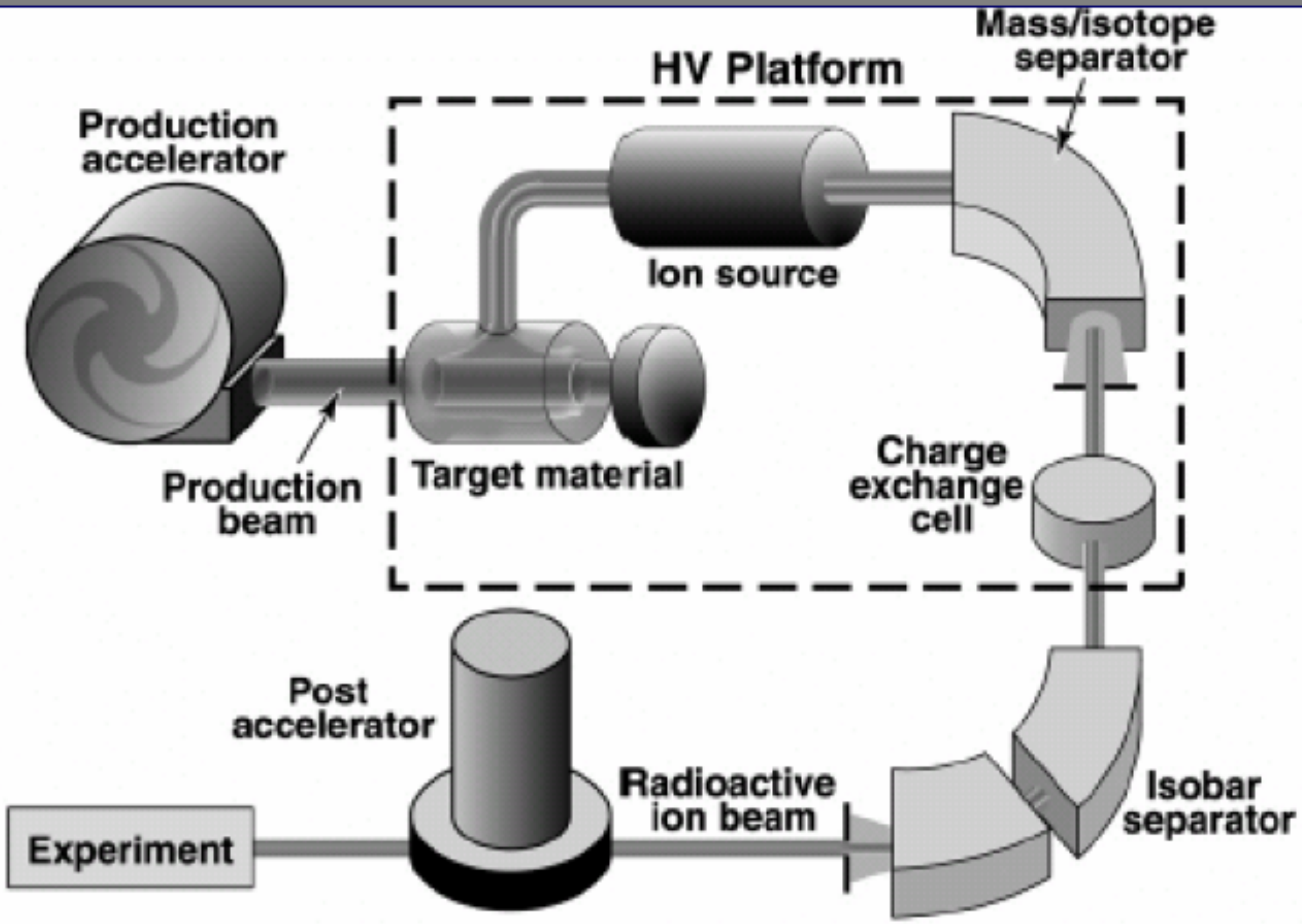


Figure 1: The Niels Bohr Institute cyclotron.

Produzione di ioni di Kr
per studiare il
decadimento beta



They were investigating beta-decay and neutrino emission from neutron-rich krypton isotopes, produced in uranium fission. Using a variant of the "converter" method – now enjoying renewed interest for the next generation of RIB facilities – they used deuterons from their cyclotron on an internal target to produce neutrons. These then struck a uranium oxide target (mixed with baking powder) from which gas flowed. The gas was then ionised, extracted from a high-voltage platform and passed through a mass-separator, which selected the krypton ions of interest.


Mass/isotope separator
HV Platform
Production accelerator
Ion source
Production beam
Target material
Charge exchange cell
Post accelerator
Radioactive ion beam
Isobar separator
Experiment

Intensità particelle prodotte

$$\boxed{I = \sigma \times \Phi \times N \times \varepsilon_1 \times \varepsilon_2 \times \varepsilon_3 \times \varepsilon_4 \times \varepsilon_5}$$

I = Intensità particelle prodotte

σ: cross-section,
Φ: primary-beam intensity,
N: target thickness,
ε_1: product release and transfer efficiency,
ε_2: ion-source efficiency,
ε_3: efficiency due to radioactive decay losses,
ε_4: efficiency of the spectrometer,
ε_5: post-accelerator efficiency.

$\Phi \times N$ = Luminosity

Metodo ISOL

Isotopes Separation On Line

- Driver ad alta intensità (Dissipazione Calore)
- Targhette di produzione (Raffreddamento e Radioattività)
- Efficienza Selezione(20%)
- Efficienza di estrazione (30%)
- Efficienza di Trasmissione alla Sorgente(30%)

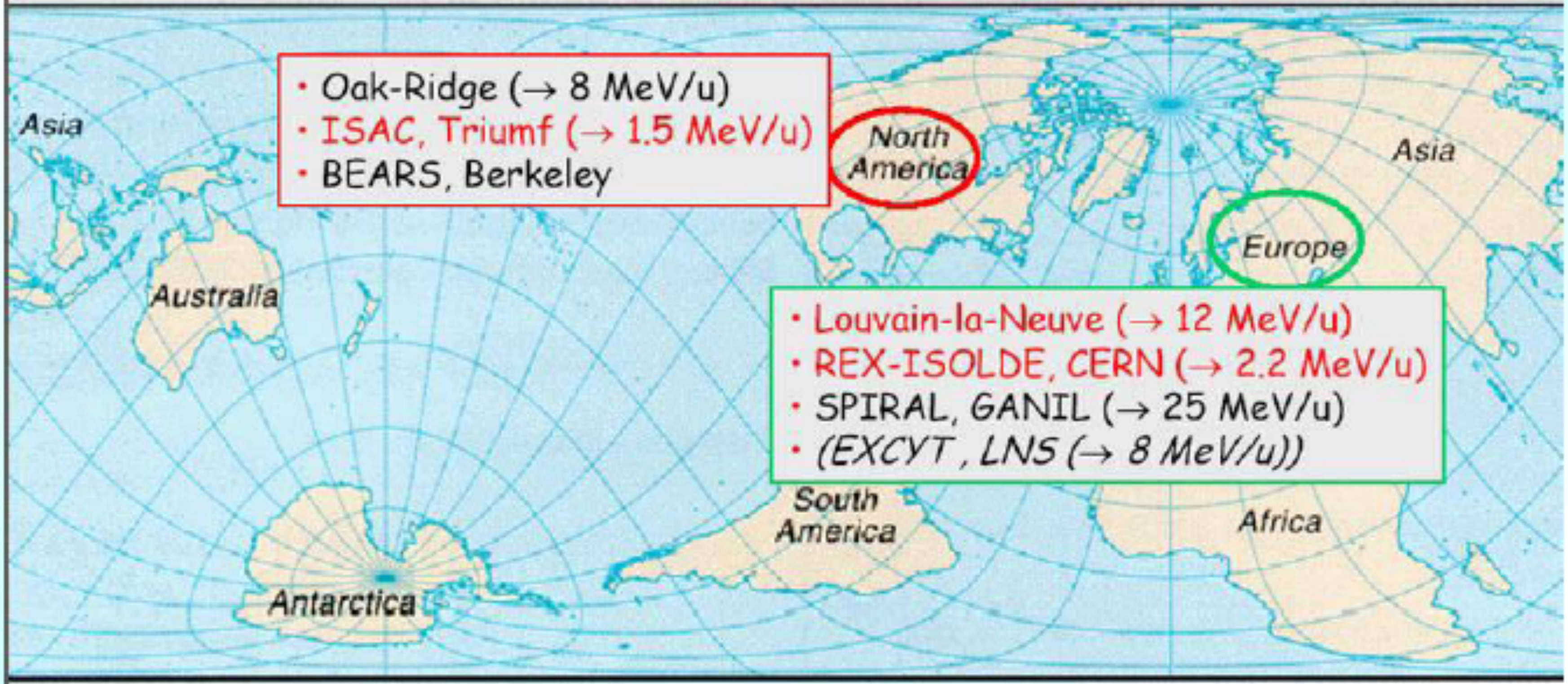
Potenza in gioco

Potenza (W)= I V = I (Energy/Charge state)

Es: I=1mA E=50 A MeV di O^{16} completamente strippato (O^{8+}) :
$P = 1\ 10^{-3}\ (50\ 16/8)\ 10^{6} = 100$ kW

Facilities of the first generation

ISOL facilities



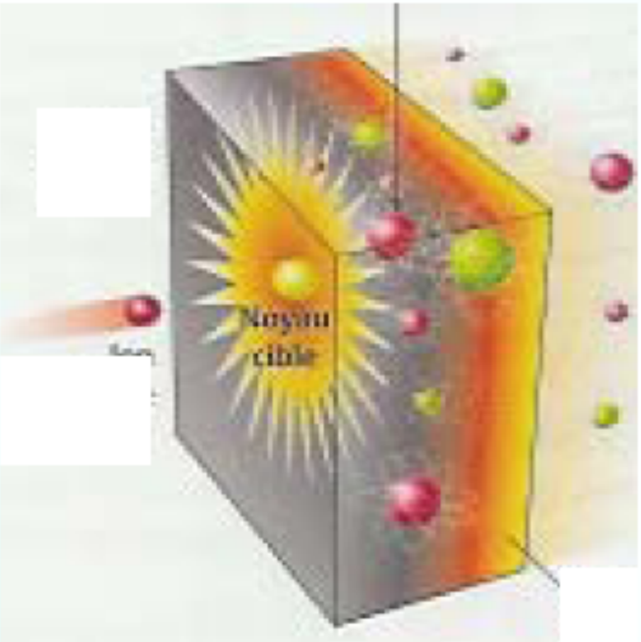
- Oak-Ridge (→ 8 MeV/u)
- ISAC, Triumf (→ 1.5 MeV/u)
- BEARS, Berkeley

- Louvain-la-Neuve (→ 12 MeV/u)
- REX-ISOLDE, CERN (→ 2.2 MeV/u)
- SPIRAL, GANIL (→ 25 MeV/u)
- *(EXCYT , LNS (→ 8 MeV/u))*

Potenze del fascio del driver primario di pochi kW

Proprieta' del bersaglio di produzione

ISOL: I nuclei prodotti dalle reazioni sono fermati nel bersaglio di produzione



Per estrarli si sfrutta il processo di effusione-diffusione nei solidi

Diffusione : e' il processo attraverso il quale la materia e' trasportata da una parte all'altra come risultato del moto molecolare di tipo random

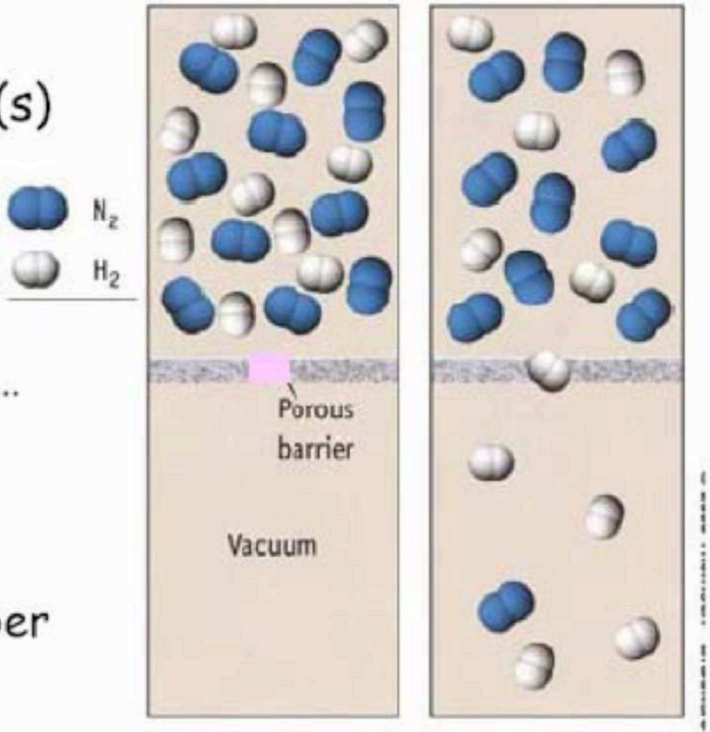
Serve un gradiente termico

Indipendentempente dal meccanismo atomico responsabile della diffusione si descrive il coefficiente di diffusione macroscopico D (che dipende dalla temperatura, e dal materiale)

+ meccanismo di effusione per uscire dalla superficie

2. Effusion

= movement of a gas through tiny hole(s)
= faster for lighter molecules…



Before effusion   During effusion

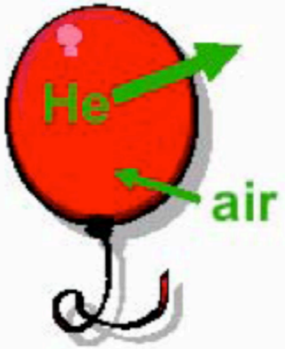
WHY DOES IT HAPPEN?

→ molecules collide with container walls…
→ but if "hit" the hole: go through!

BALLOONS:

- molecules effuse through holes in rubber
- rate (= moles/time) is:
  proportional to temperature
  inversely proportional to molar mass.

Thus: a He balloon deflates after a while…
He effuses out more rapidly than
N_2 & O_2 from air effuse in.



ISOL : SERVE UN BERSAGLIO CON BUONA POROSITA' !

Efficienza di diffusion-effusion da temperatura

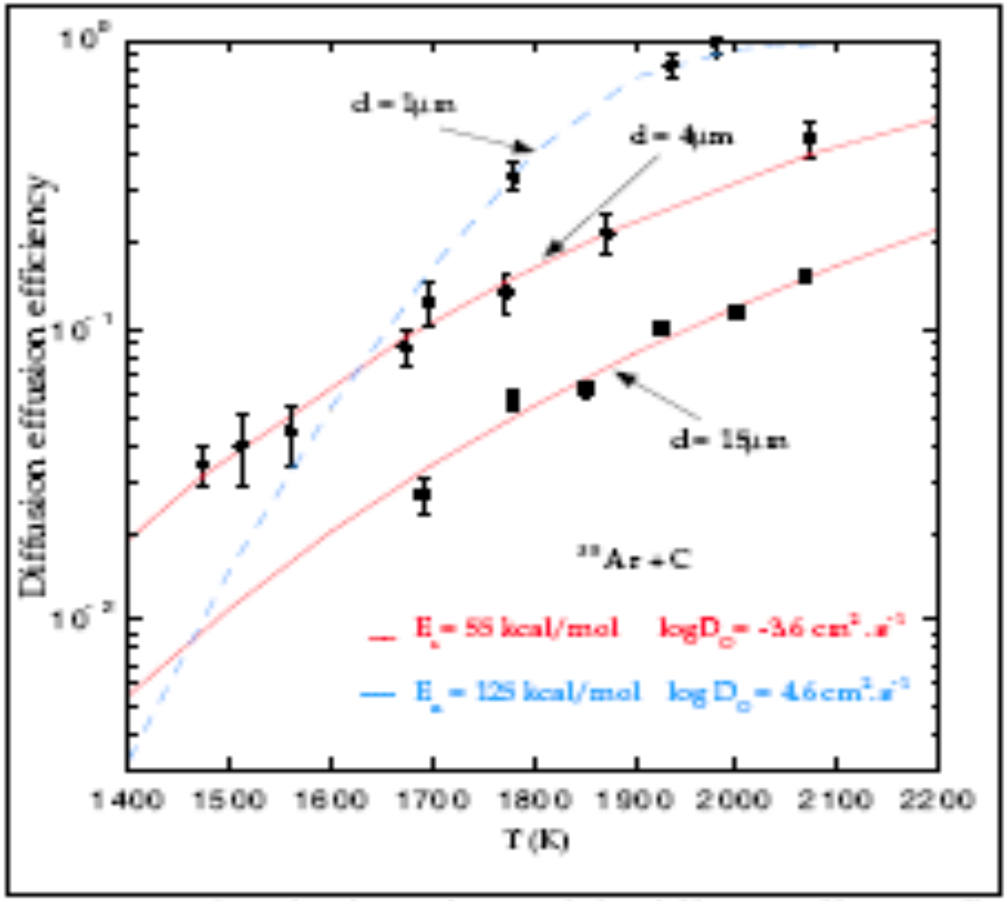


Figure 4 : Picture of the carbon targets : (left) the target dedicated to Ar and Ne production; (right) the target dedicated to He production.

Multi-slice target

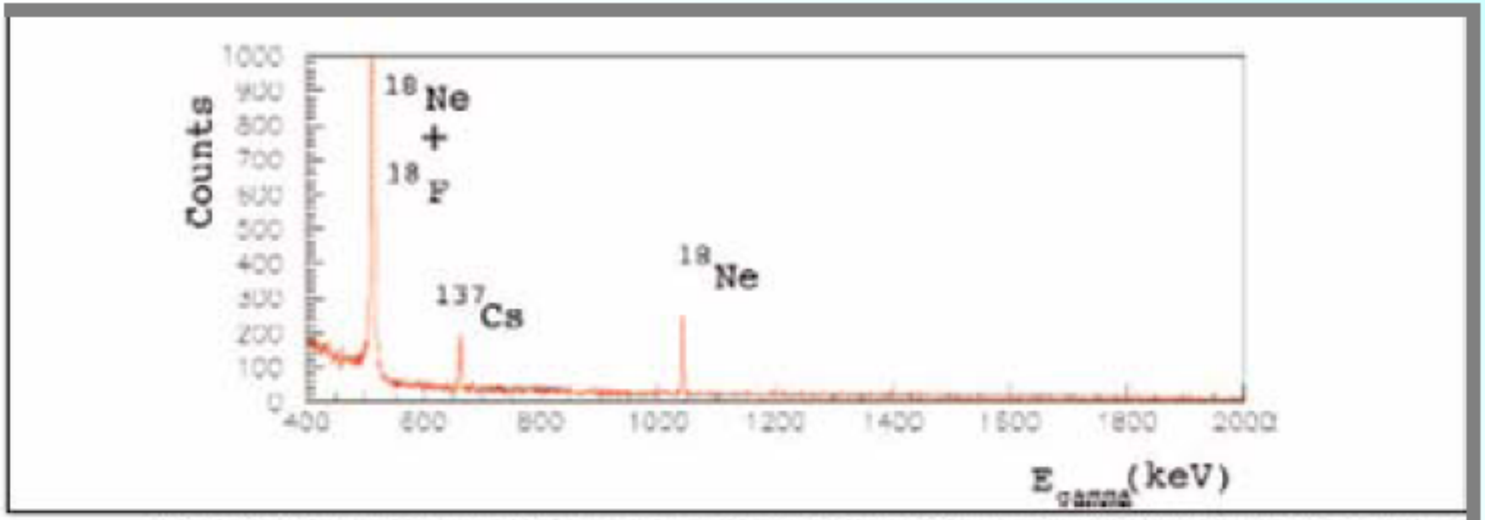


Figure 3 : Energy spectrum of the germanium detector during the first experiment at SPIRAL. The ^{18}Ne is clearly identified with the 1041 keV gamma ray. The 671 keV is emitted by the ^{137}Cs of the calibration source used.

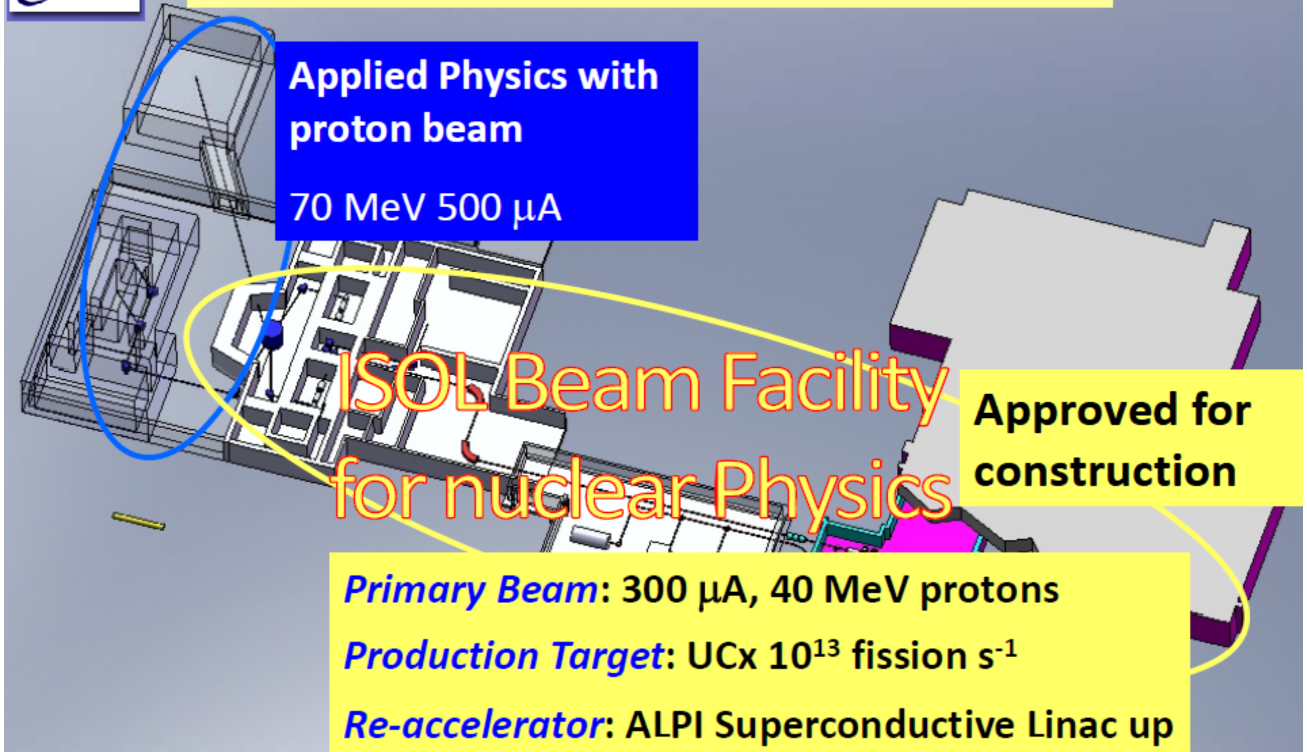
Check beam purity with gamma spectroscopy!

Ottima qualità dei Fasci ISOL

SPES

A Mid-term RNB Facility Based on a 40 MeV Proton Driver and on the Multi-Slice Direct Target Concept

The SPES Project @ LNL: a multi-user project



Applied Physics with proton beam

70 MeV 500 µA

ISOL Beam Facility for nuclear Physics

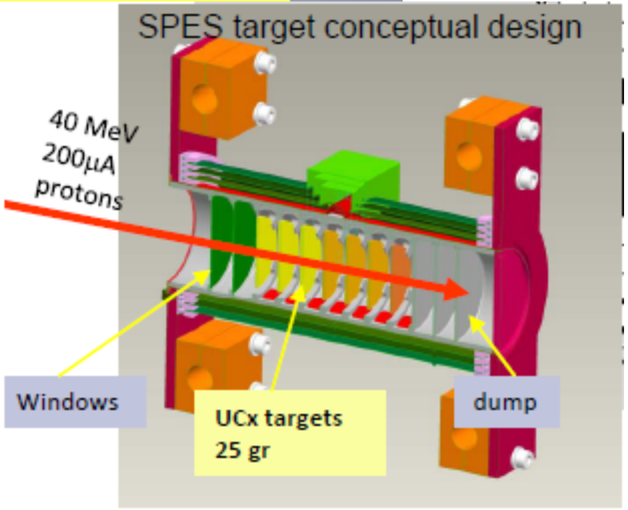
Approved for construction

***Primary Beam*: 300 µA, 40 MeV protons**

***Production Target*: UCx 10^{13} fission s^{-1}**

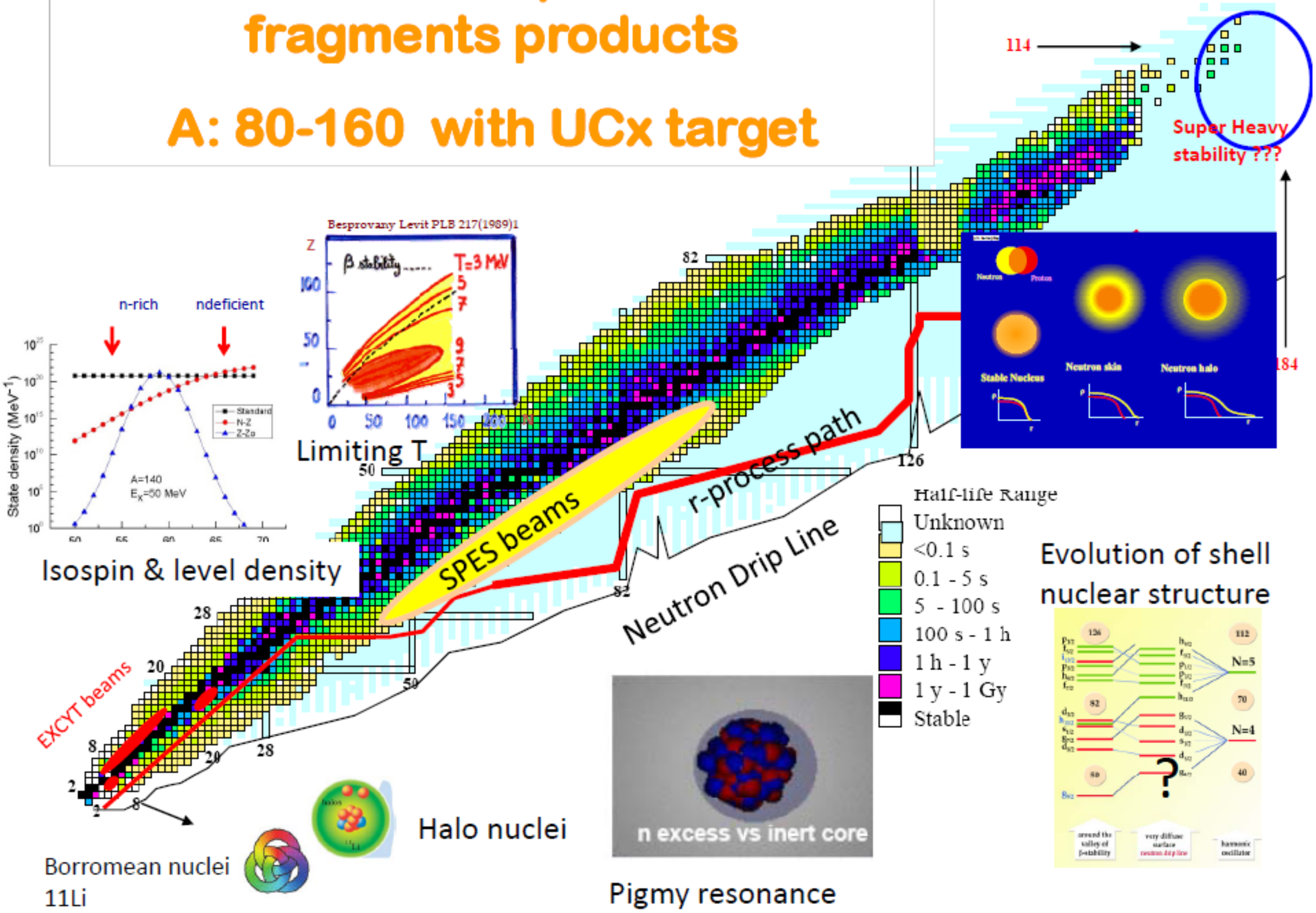
***Re-accelerator*: ALPI Superconductive Linac up to 11 AMeV for A=130**

ISOL target operated at 2000°C. Ionization and extraction with 1+ Plasma Source.



Neutron Rich Isotopes are fission fragments products

A: 80-160 with UCx target



Isospin & level density

Limiting T

Evolution of shell nuclear structure

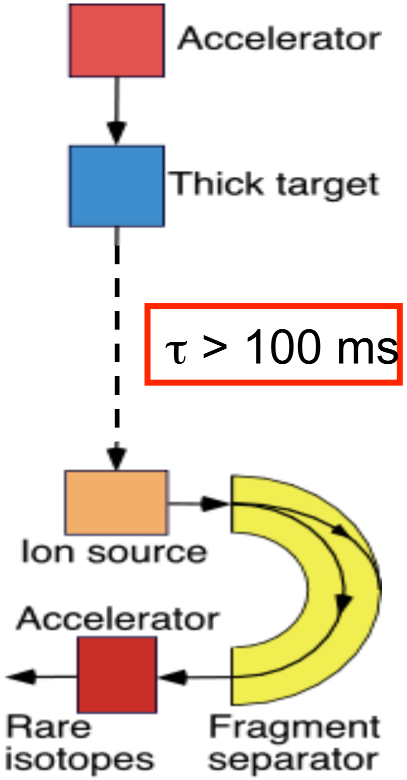
Halo nuclei

Pigmy resonance

Borromean nuclei
11Li

Radioactive Beams

ISOL (Isotope Separation on Line)



$\tau > 100$ ms

high intensity beam
p,He

- **heavy elements**
- target nuclei break into fragments (desired isotopes)
- fragments are extracted heating the target to high T (diffusion process)

- diffused atoms are collected
- ionized
- separated
- re-accelerated

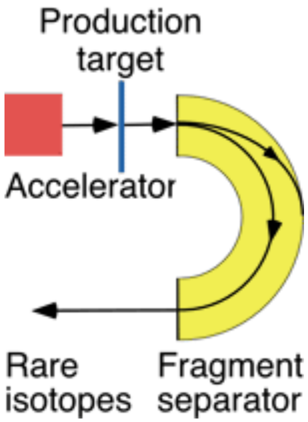
Advantages: excellent beam quality

Disadvantages: development of diffusion process for each elements

Rex-Isolde: 3.1 MeV/A (Z=2-88), ≈10^4-10^{11} ions/s
Spiral: 1.7-25 MeV/A (Z=2-36), up to 10^{11} ions/s
Spes: 20 MeV/A (Z=80-160), up to 10^9 ions/s

In-Flight (Fragmentation)

- high intensity beam of **heavy elements** hits thin production target
- beam atoms fragment into smaller atoms
- fragments proceed with same speed and are separate by a magnet



Relativstic beams, forward focus

Advantages:
no chemical processes involved,
high-intensity beams

$\tau < 1\ \mu s$

GSI: fast beams ≥ 50 MeV/A
RIA: primary beams: 400MeV/A
up to 1pμA
RIKEN: primary beams: 400MeV/A
up to 1pμA (first phase:May 2005)

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