Lezione 1

Fasci Radioattivi

Metodi di Produzione: In-Flight, ISOL

In Flight: David J. Morrissey and Brad M. Sherrill,
"In-Flight Separation of Projectile Fragments"
The Euroschool Lectures on Physics with Exotic Beams, Vol. 1 , Springer-Verlag (2004)

ISOL: P. Butler,
"ISOL techniques to reach radioactive nuclei – from birth to EURISOL"
Fermi School "From the Big-Bang to the nucleosynthesis" Varenna 19-24 July 2010

Additional Material: https://w.fys.kuleuven.be/wps/euroschool/lecture-notes/

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.

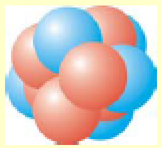
- Λ (10^{-10}sec)
- Ξ (10^{-10}sec)
- Li^{11} (neutron rich)
- Sn^{107} (proton-rich)

barioni

nuclei

Cos'e' un nucleo esotico?

Normal Nucleus:



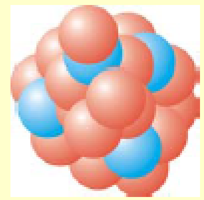
6 neutrons

6 protons (carbon)

^{12}C

Stable, found in nature

Exotic Nucleus:



16 neutrons

6 protons (carbon)

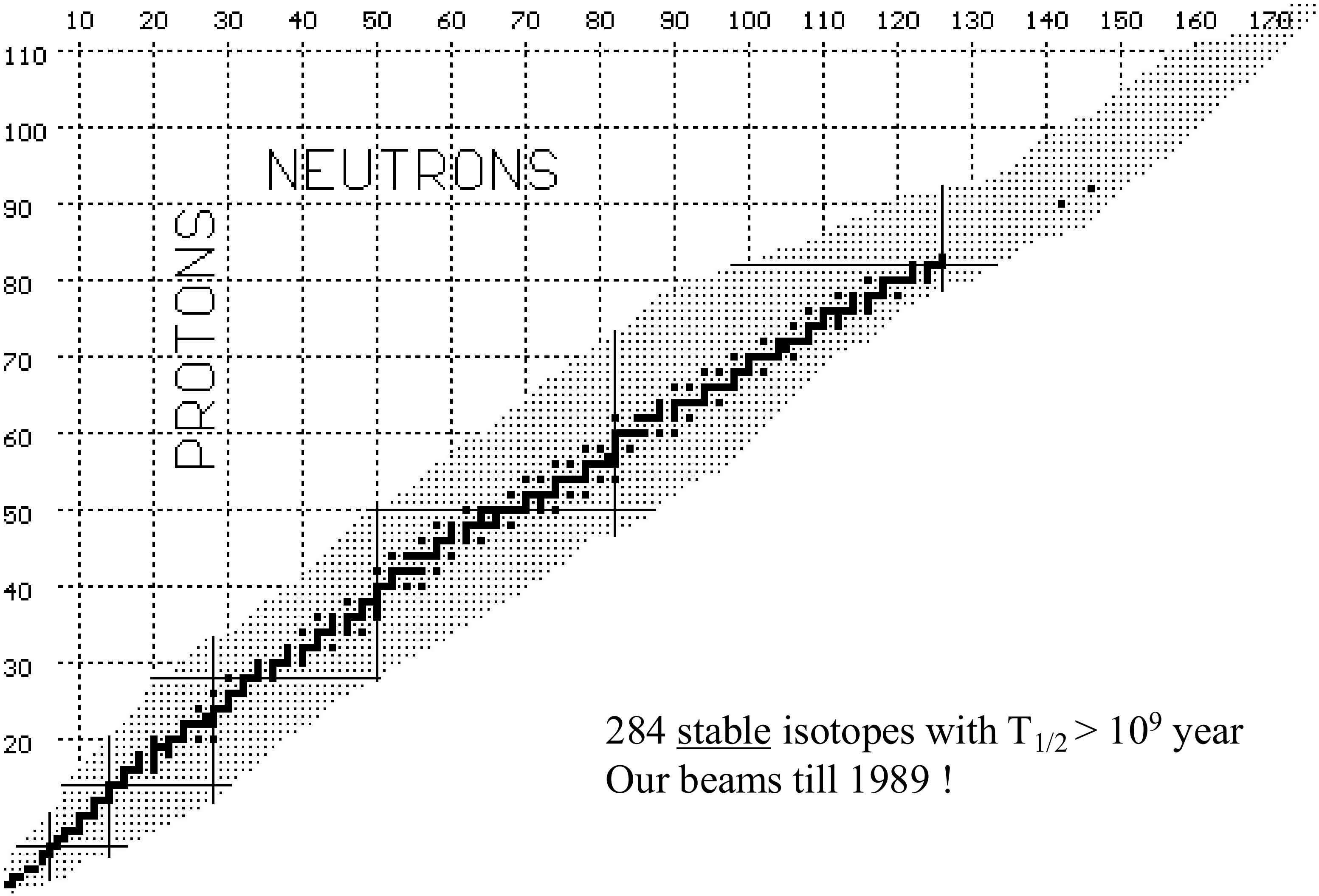
^{22}C

Radioactive, at the limit of nuclear binding

Characteristics of exotic nuclei:

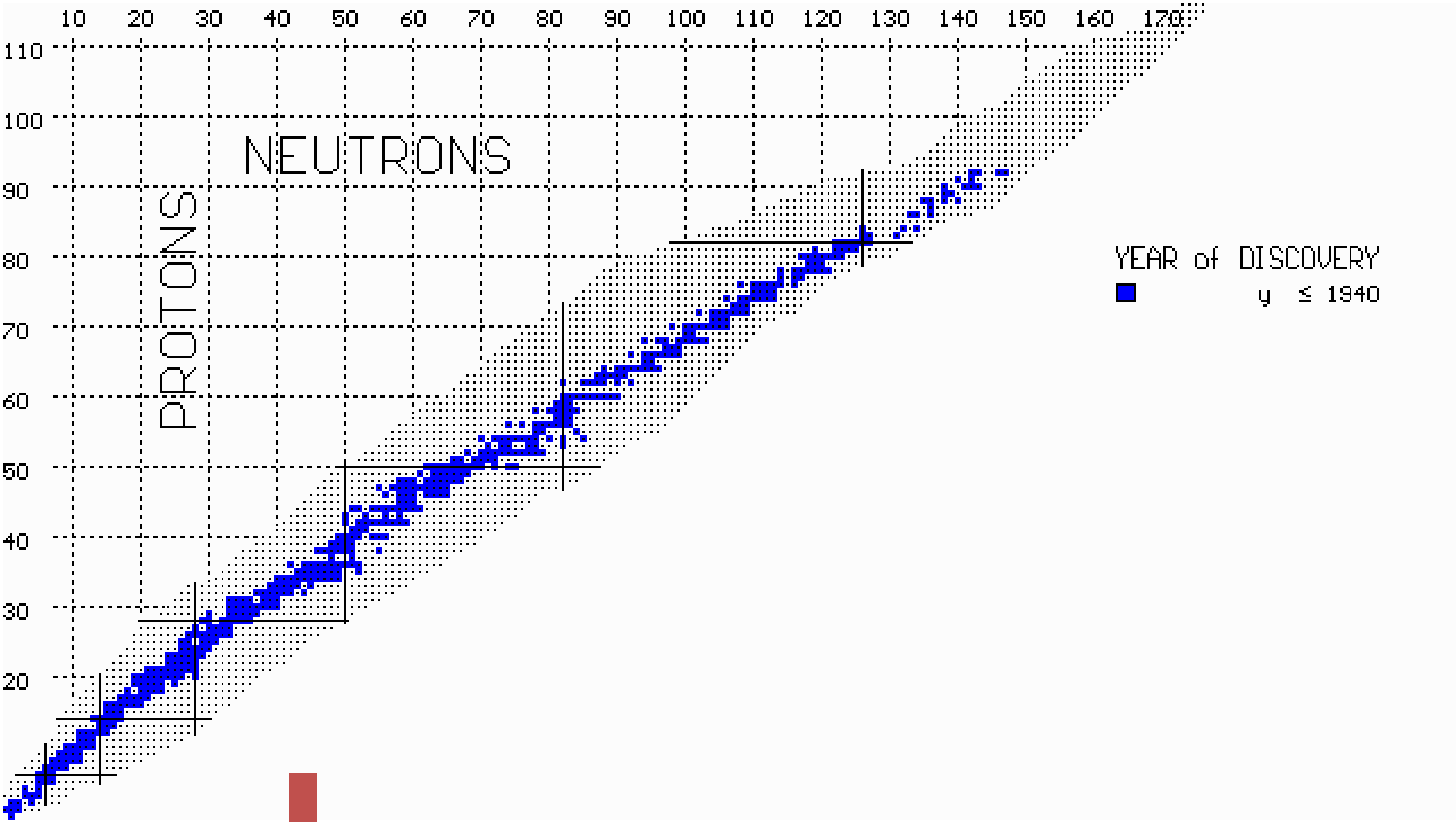
- ✓ Excess of neutrons or protons,
- ✓ short half-life,
- ✓ neutron or proton dominated surface,
- ✓ low binding

Un po' di Storia…



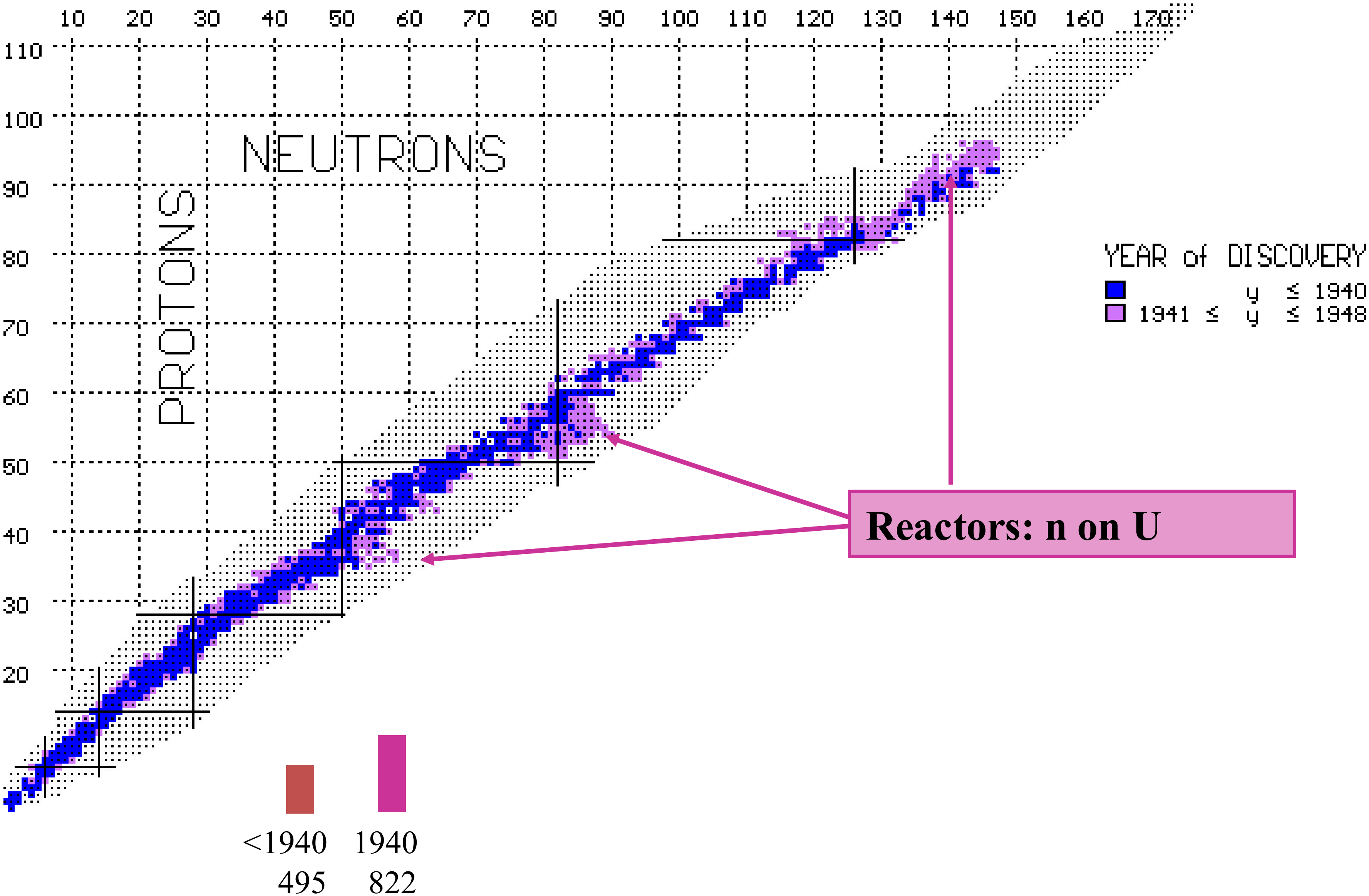
284 <u>stable</u> isotopes with $T_{1/2} > 10^9$ year
Our beams till 1989 !

Un po' di Storia…

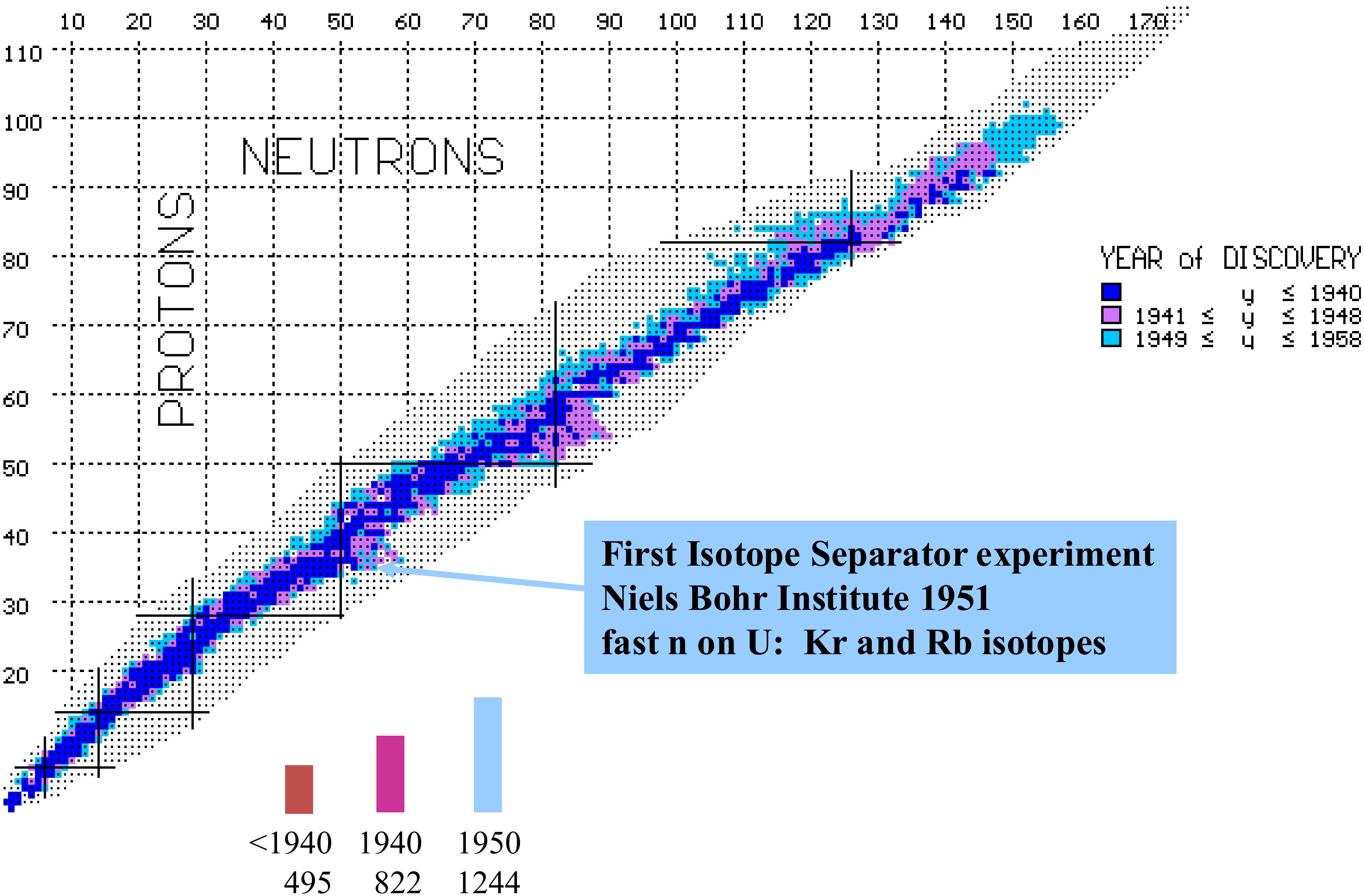


<1940
495

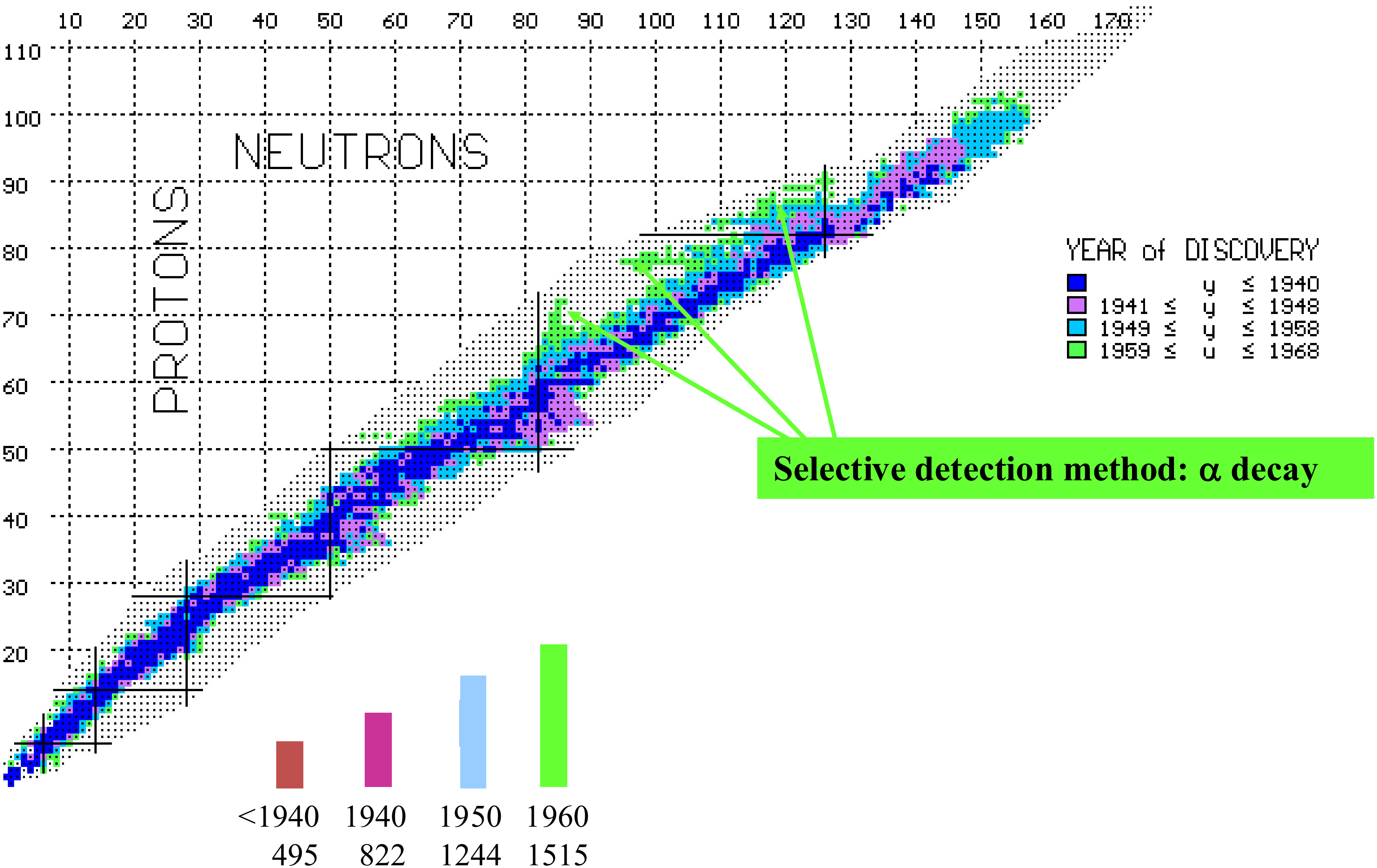
Un po' di Storia…



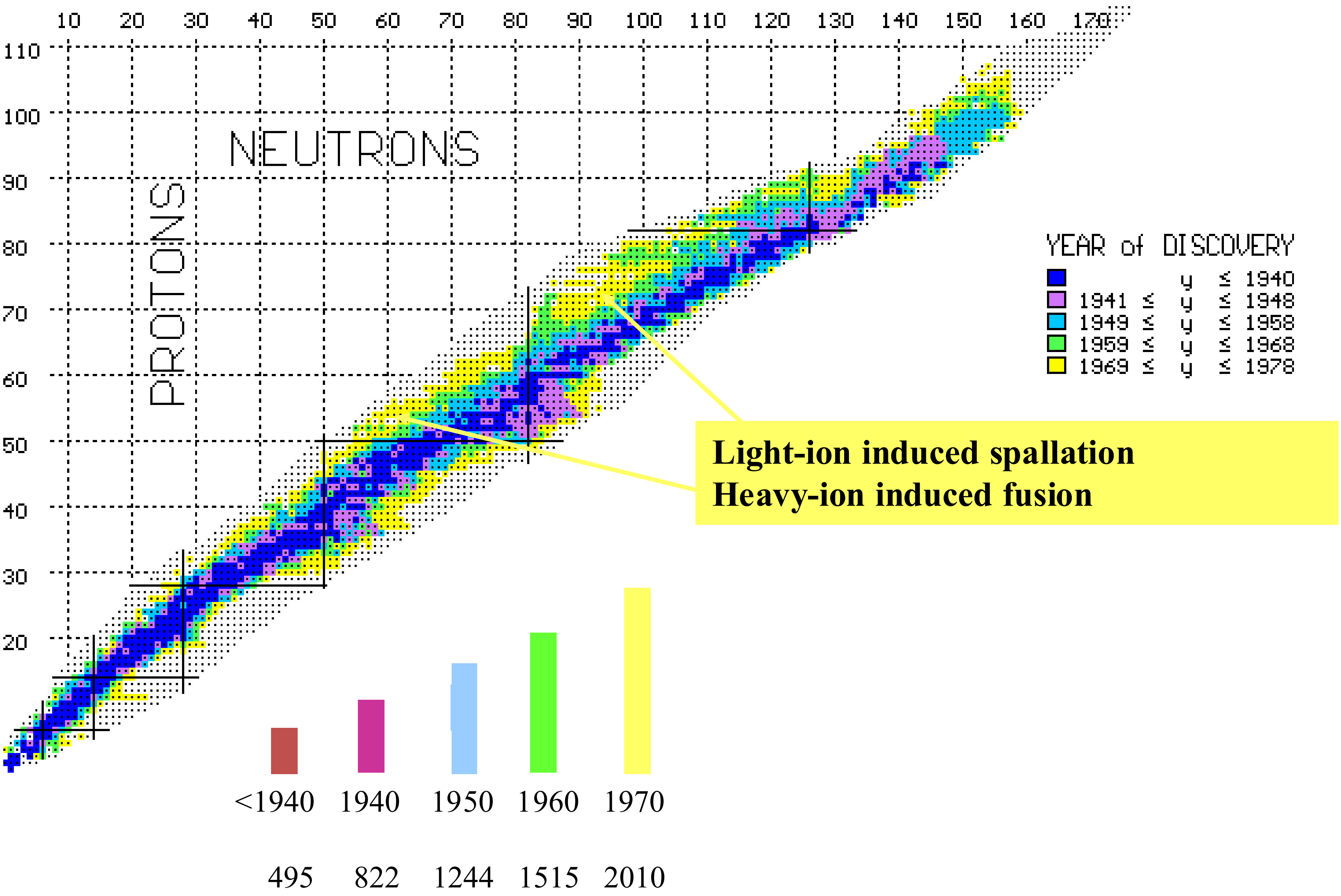
Un po' di Storia…



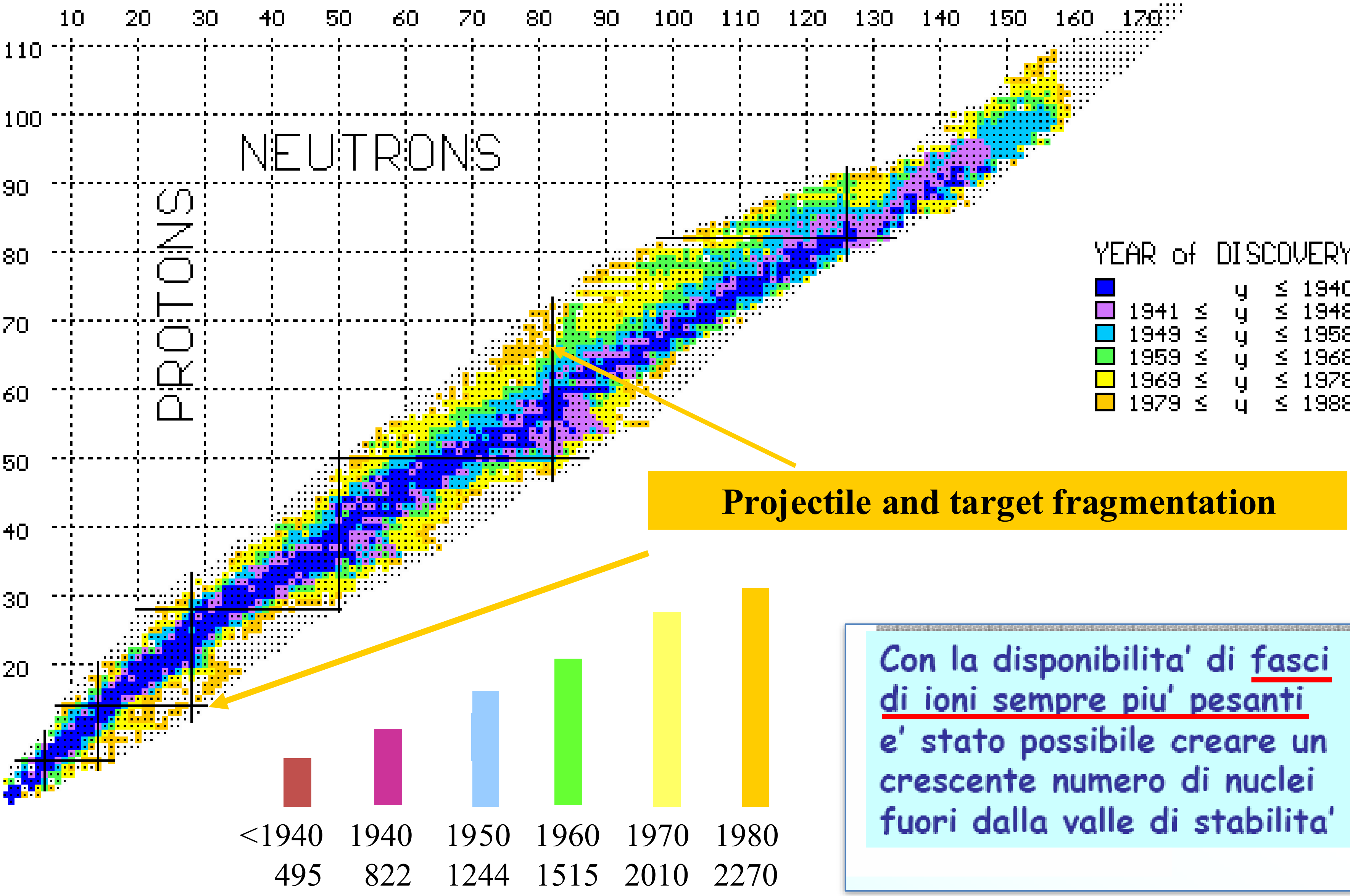
Un po' di Storia…



Un po' di Storia…



Un po' di Storia…



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

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 M AY 2 0 1 1 | VO L 4 7 3 | N AT U R E | 2 5

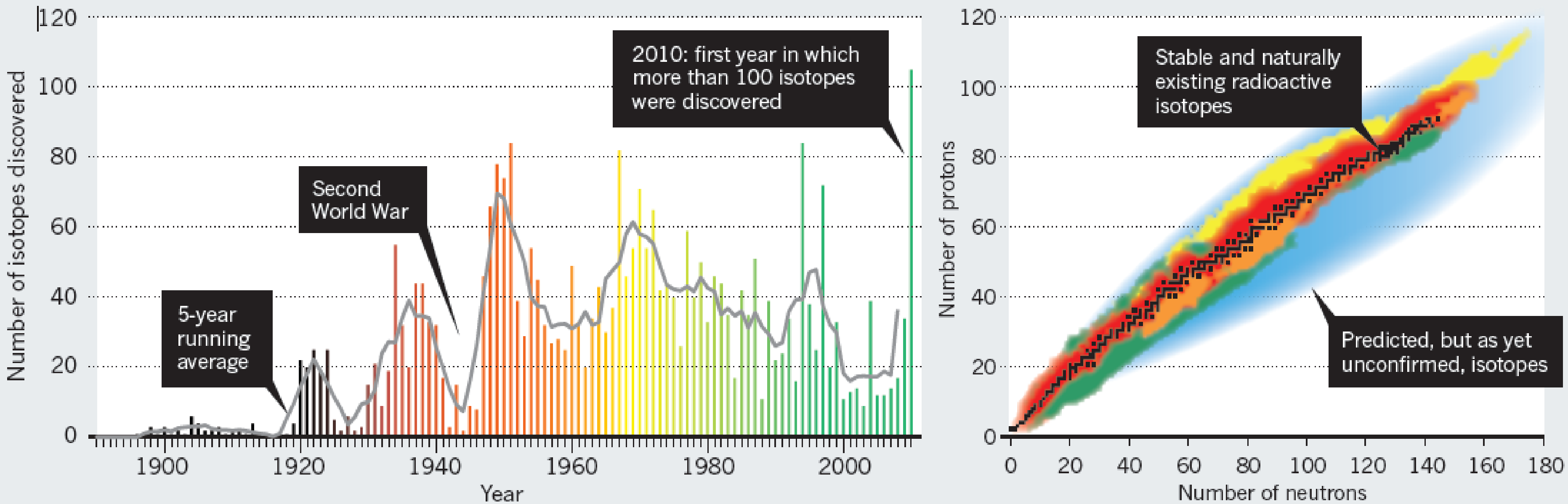
In occasion of Rutherford centennial 2011

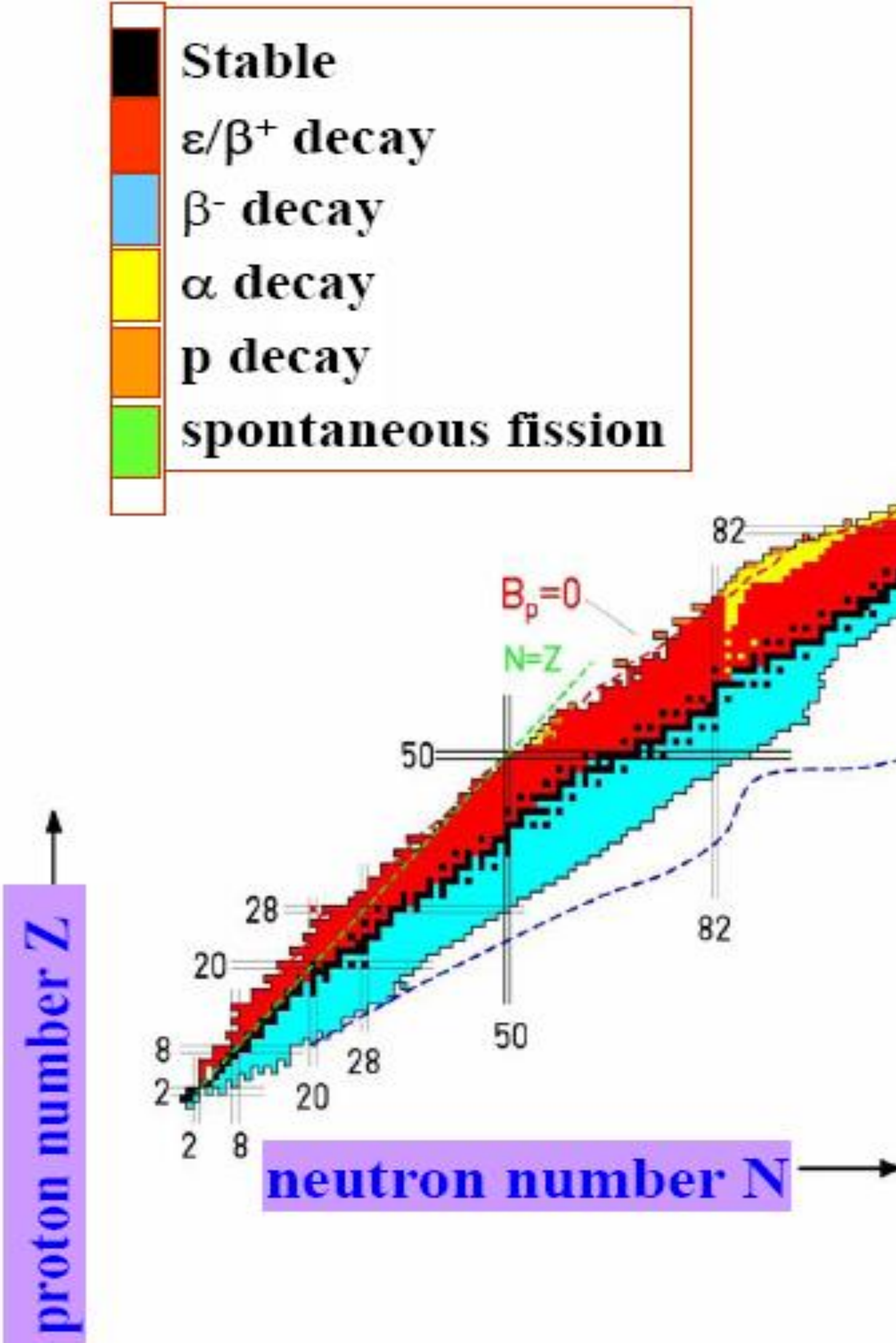
From isotopes to the stars

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



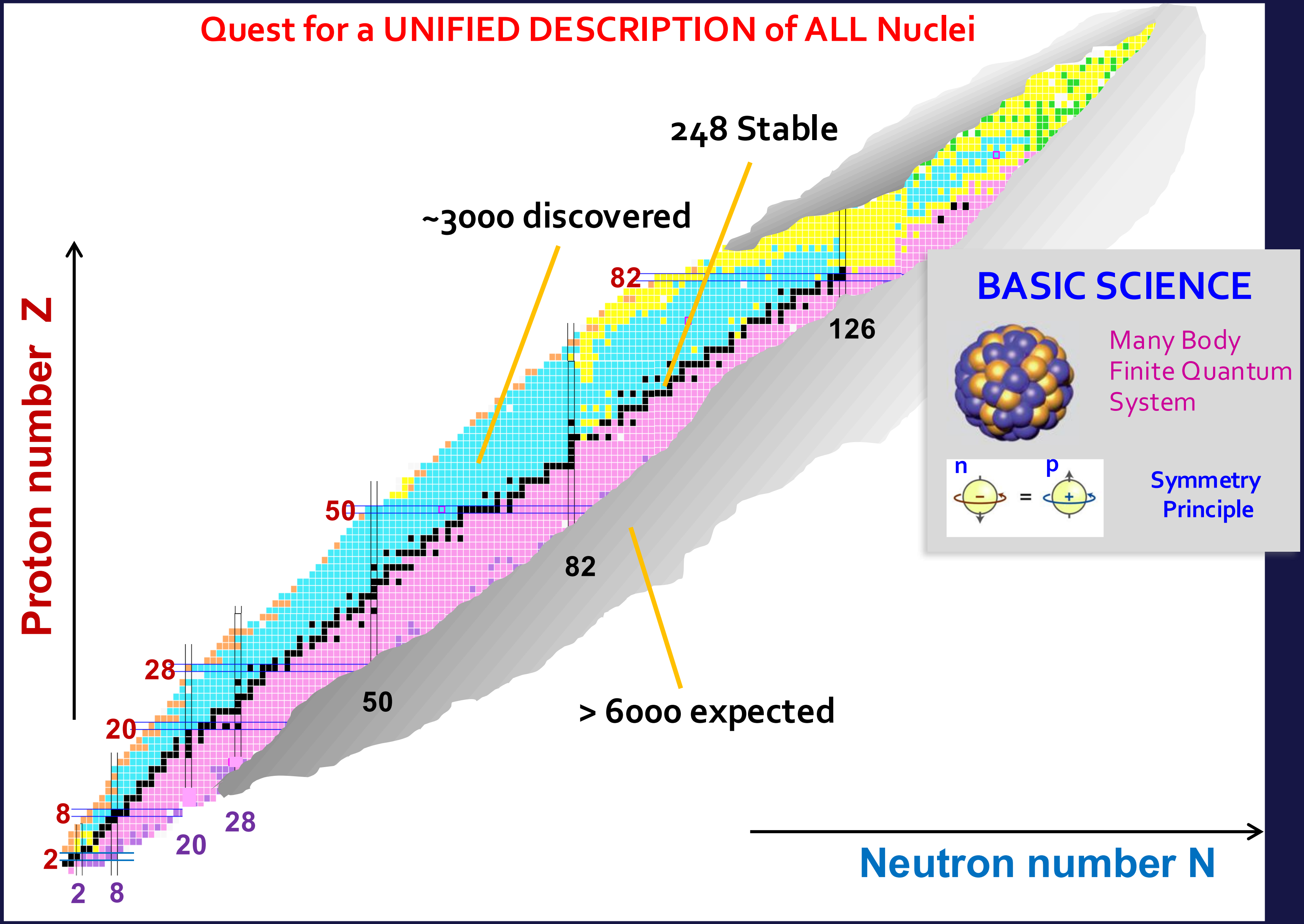


TODAY:

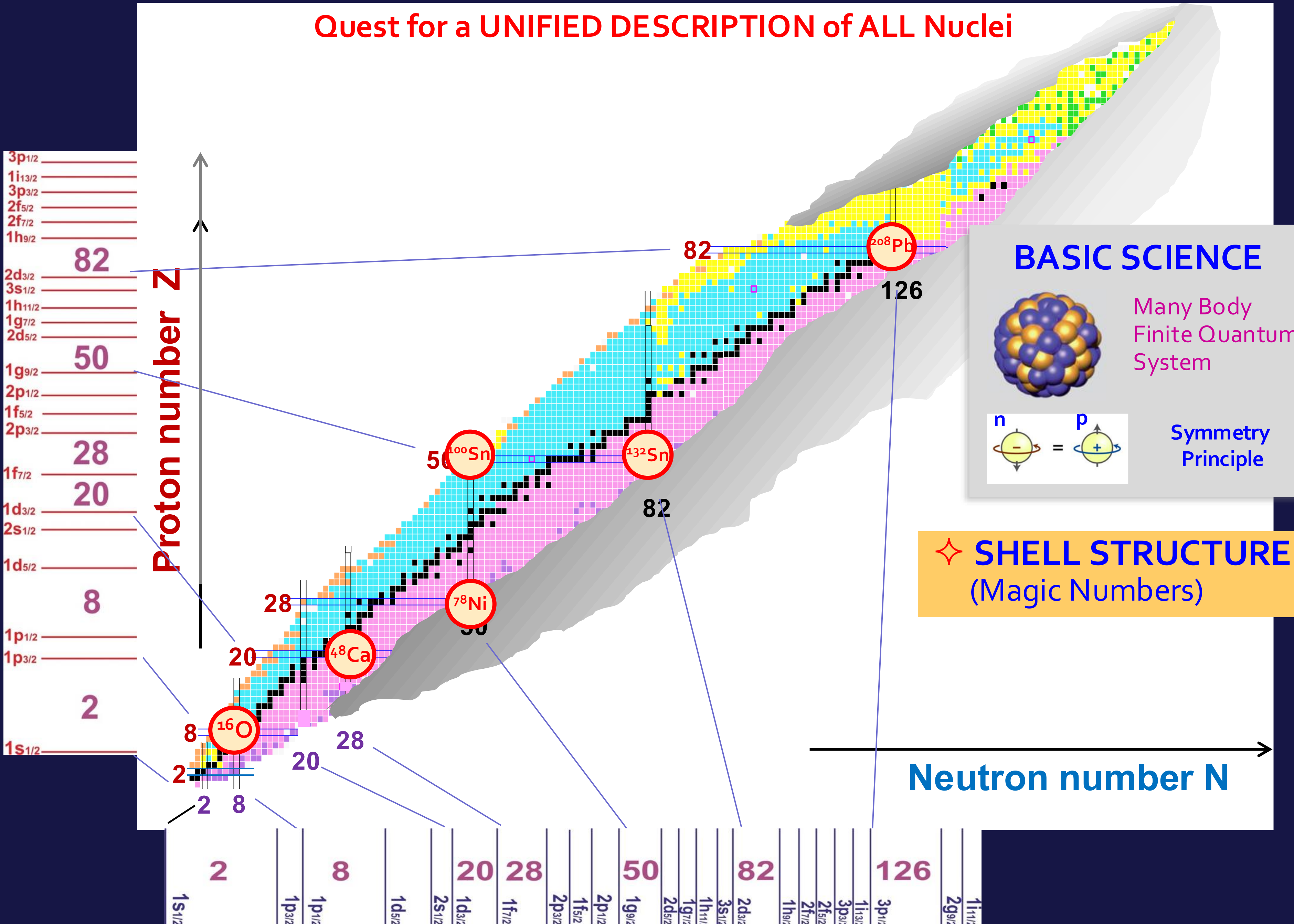
Around 3000 of the expected > 6000 nuclei have been observed

Different Decay Modes

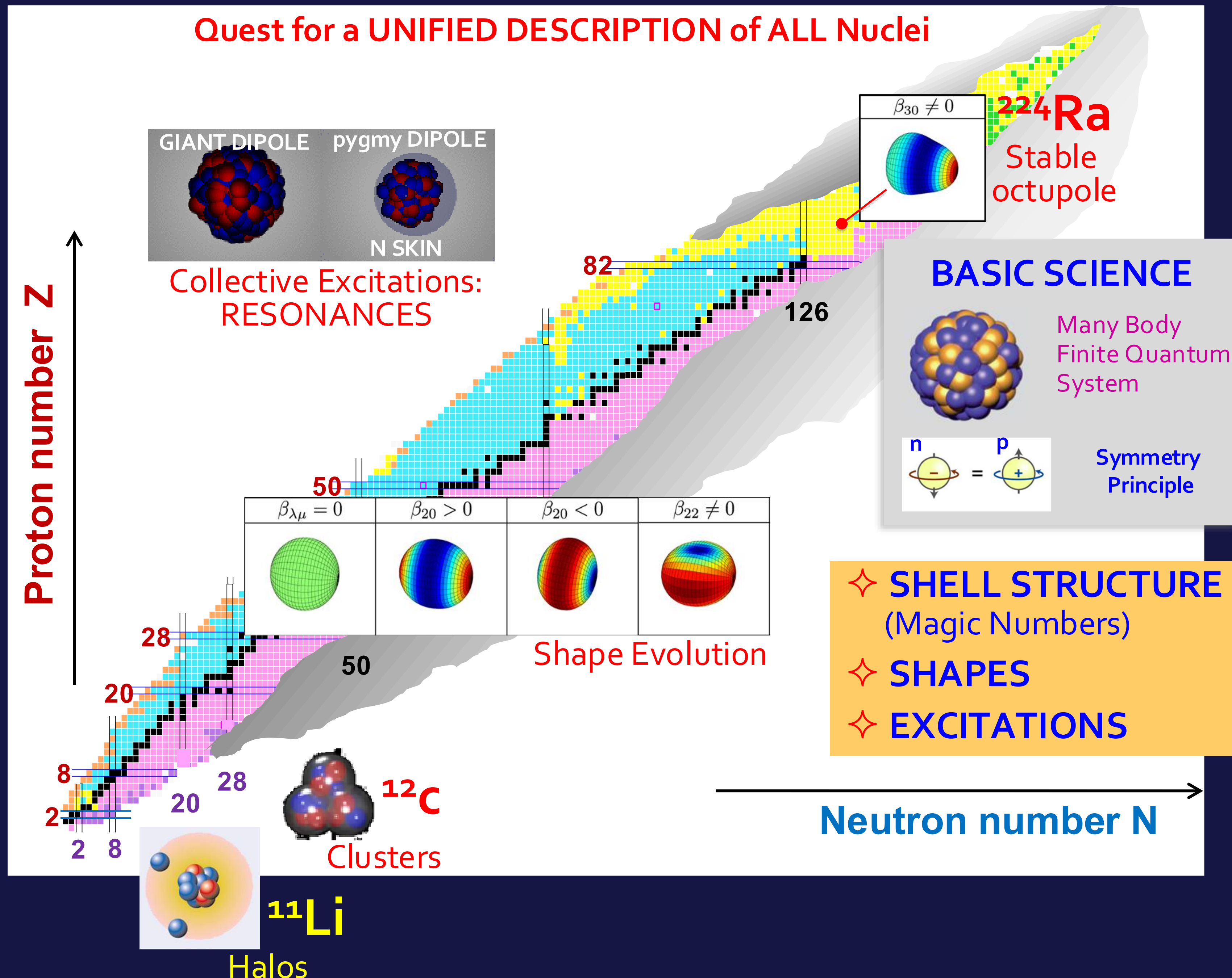
Challenges in MODERN NUCLEAR PHYSICS



Challenges in MODERN NUCLEAR PHYSICS



Challenges in MODERN NUCLEAR PHYSICS



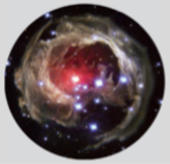
Challenges in MODERN NUCLEAR PHYSICS

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

INTERDISCIPLINARITY

Astrophysics

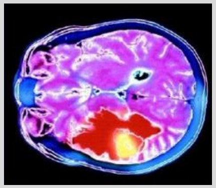
Nucleosynthesis

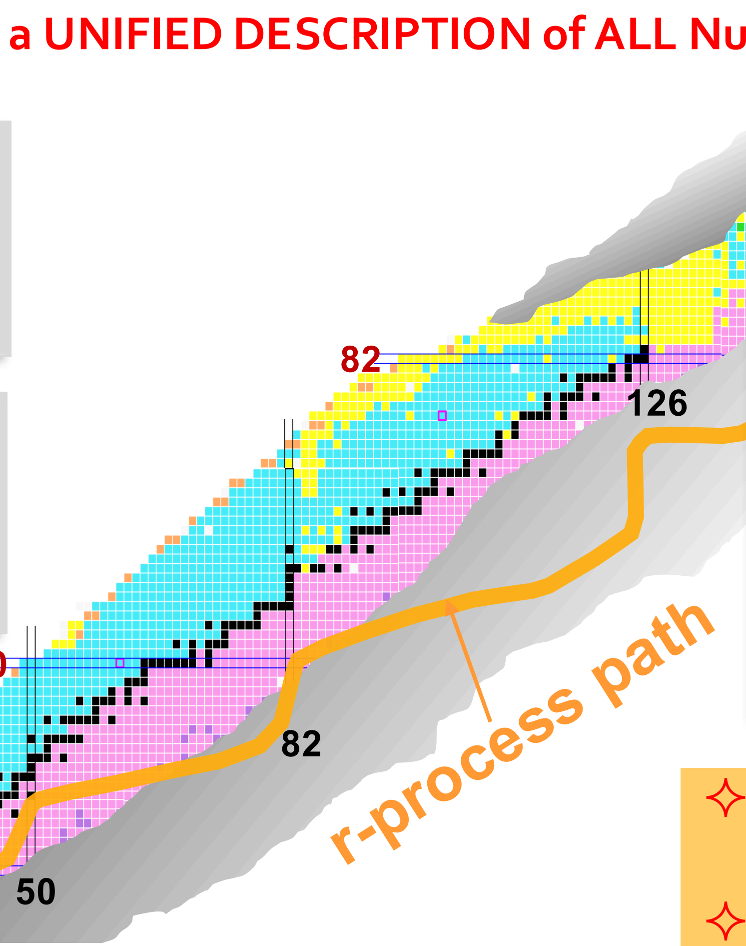


Applications

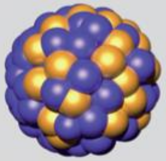
Radioisotopes,

Reactors, ...





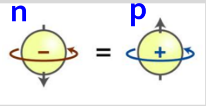
BASIC SCIENCE



Many Body

Finite Quantum

System

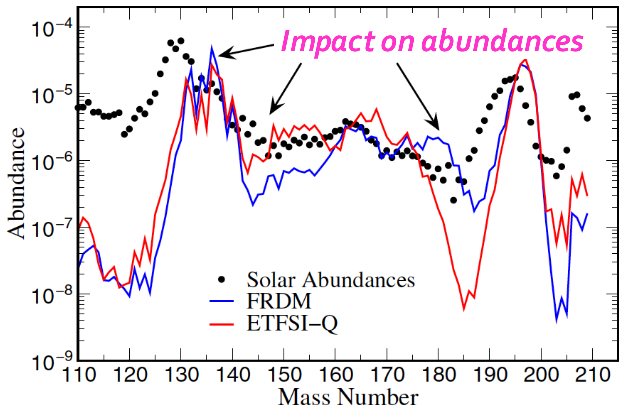


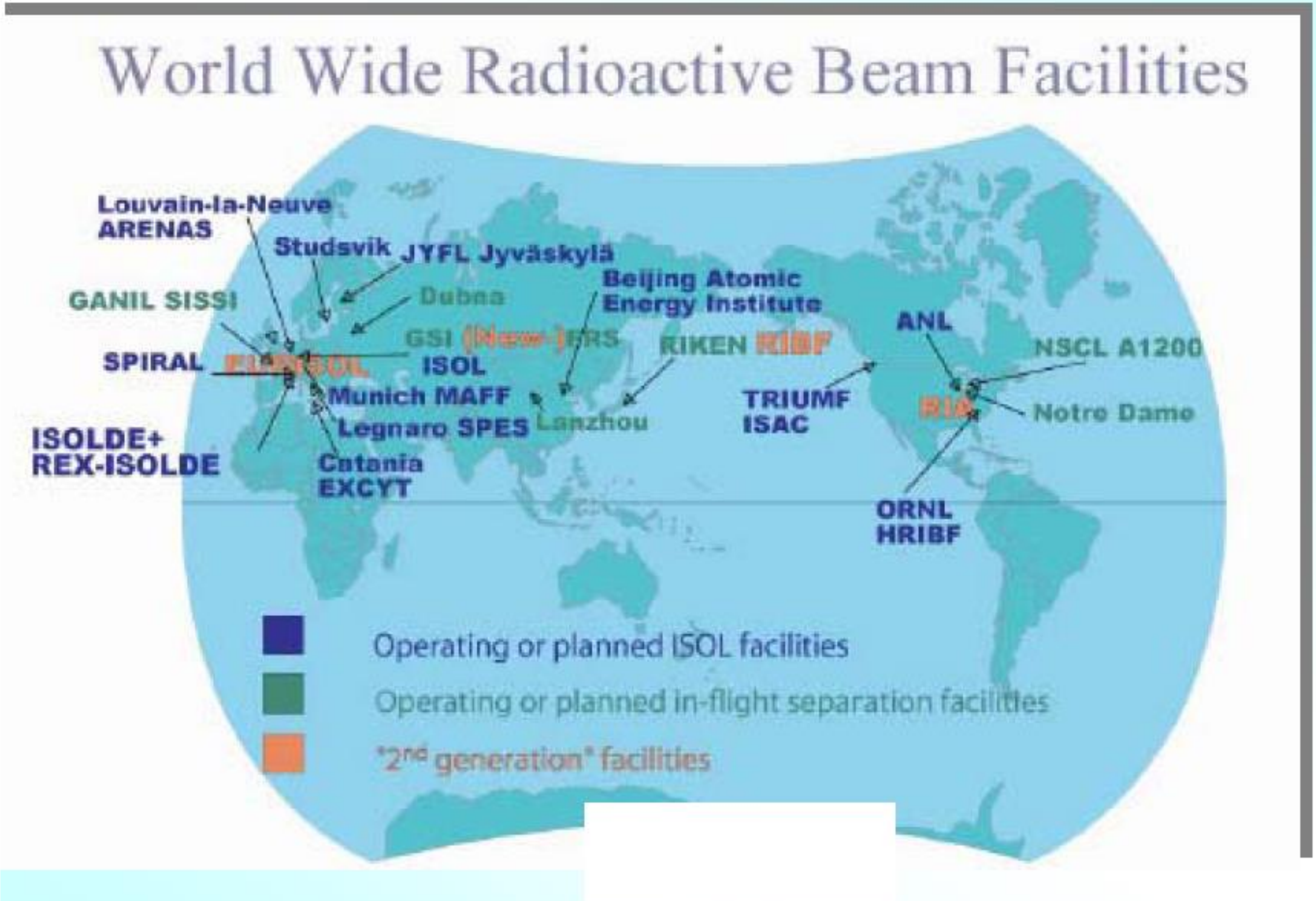
Symmetry

Principle

- ✧ **SHELL STRUCTURE** (Magic Numbers)
- ✧ **SHAPES**
- ✧ **EXCITATIONS**

Element ABUNDANCES





1. Production of exotic nuclei

2. Study of their excitations and decay modes

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)

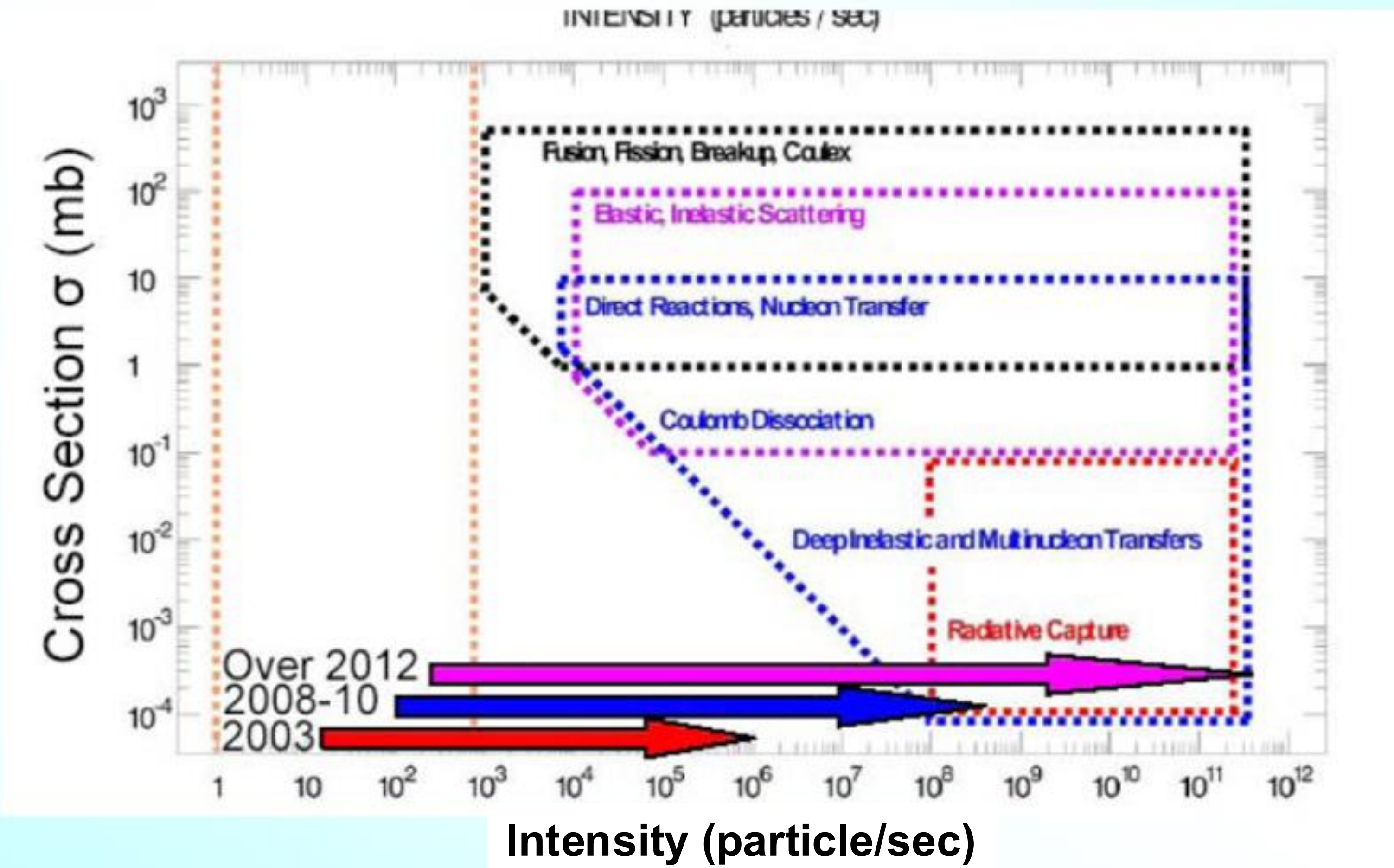
Alte energie (E> 50 MeV/U)

  Knock out , frammentazione

  eccitazione coulombiana

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

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



Intensità Minime di RIB

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

basic properties

First excited states

basic properties *(via selective techniques)*

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' ? di fasci primari

Tipico calcolo di count rate

(usato per pianificare esperimenti)

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

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

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

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

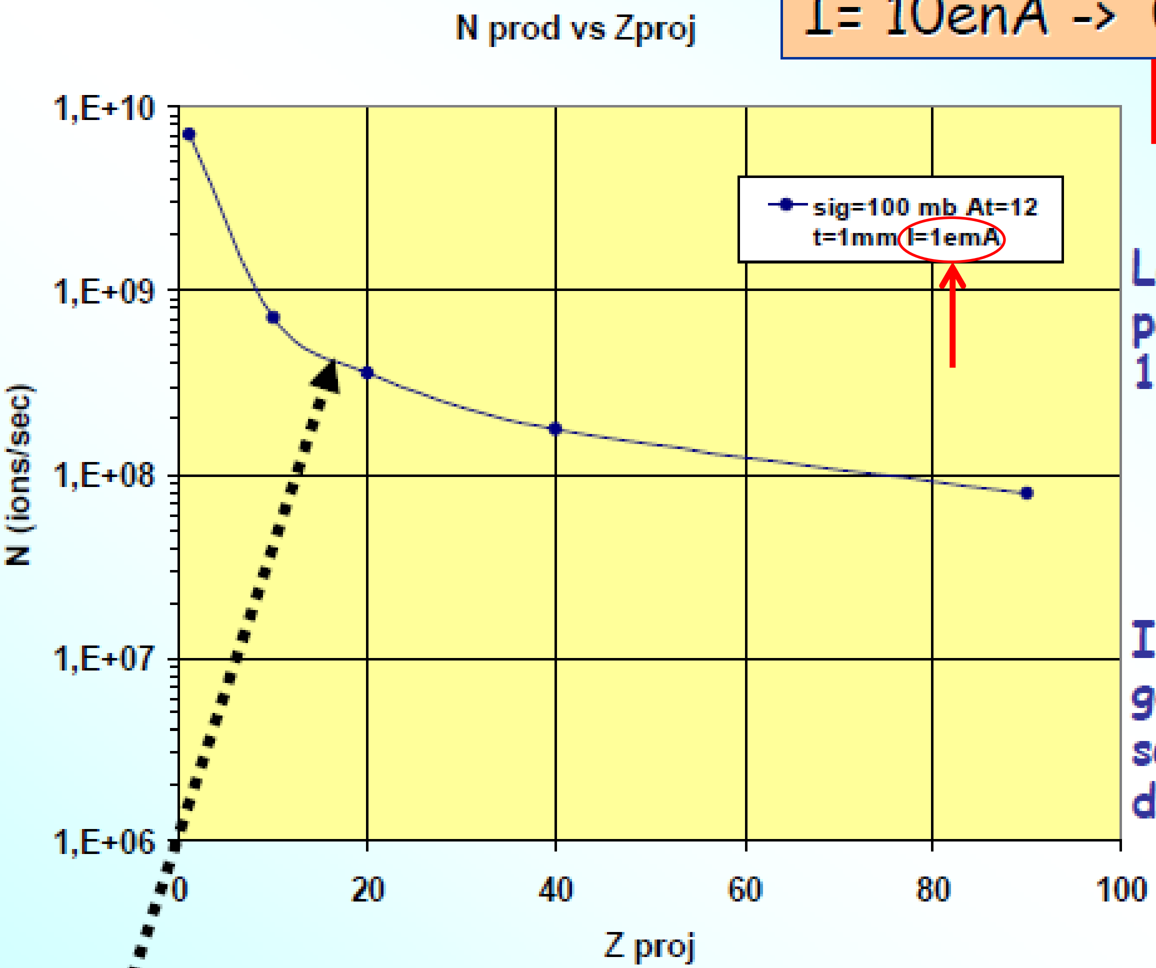
$$N_{prod} = \frac{3.76\;\; I(enA)\,\chi\,[\mu gr/cm^2]\,\sigma\,[mbarn]}{Z_{proj}\,A_{targ}}$$

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

Esempio : ρ= 2 gr/ cm³ e t= 1 mm χ =2 10^5 μgr/cm² = 200 mg/cm²

$I = 10 \text{enA} \rightarrow 0.6 \ 10^{11}$ protons/sec

1 particle nA = 6.25×10^9 pps



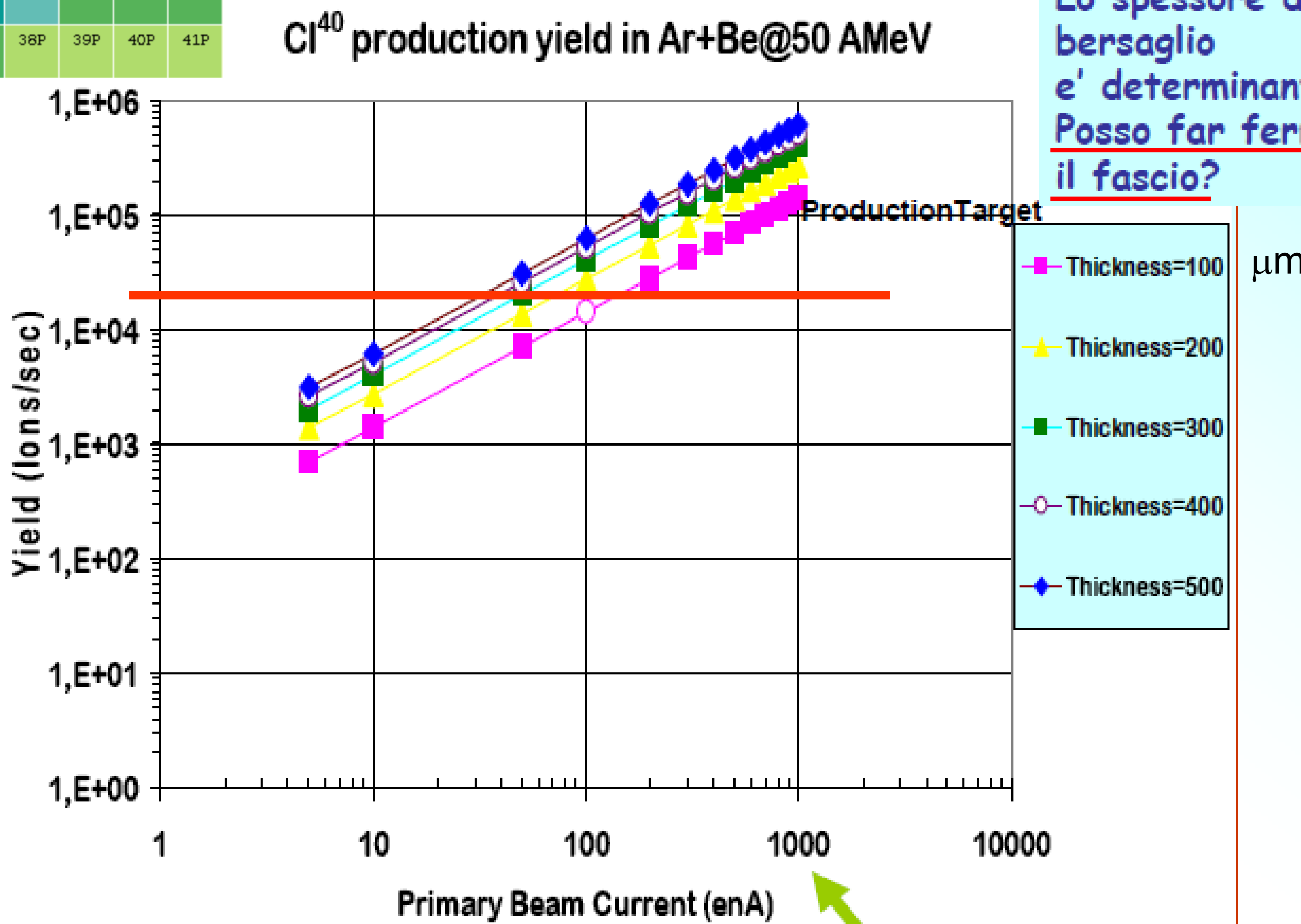
La fisica con i fasci di ioni pesanti si fa con intensita' 10^9-10^{11} ioni al secondo

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

38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar
37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl
36S	37S	38S	39S	40S	41S	42S
35P	36P	37P	38P	39P	40P	41P



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

≈ 1 kWatt

Fasci radioattivi prodotti utilizzando <u>ioni pesanti</u>

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

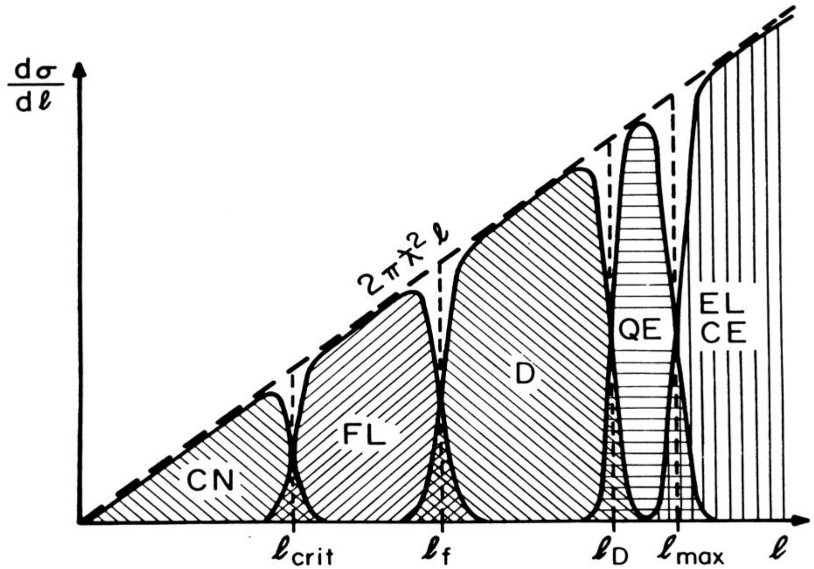
- Se aumento l'energia in modo da poter fare uscire i prodotti dal bersaglio cambiano i meccanismi di produzione !

✓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



Angular momentum transferred

Figure 39. Schematic illustration of the l dependence of the partial cross section for compound-nucleus (CN), fusion-like (FL), damped (D), quasielastic (QE), Coulomb-excitation (CE), and elastic (EL) processes. The long-dashed line represents the geometrical partial cross section $d\sigma/dl = 2\pi ƛ^2 l$. Vertical dashed lines indicate the extensions of the various l windows in a sharp cutoff model with the characteristic l values noted at the abscissa. Hatched areas represent the diffuse l windows assumed in a smooth cutoff model.

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

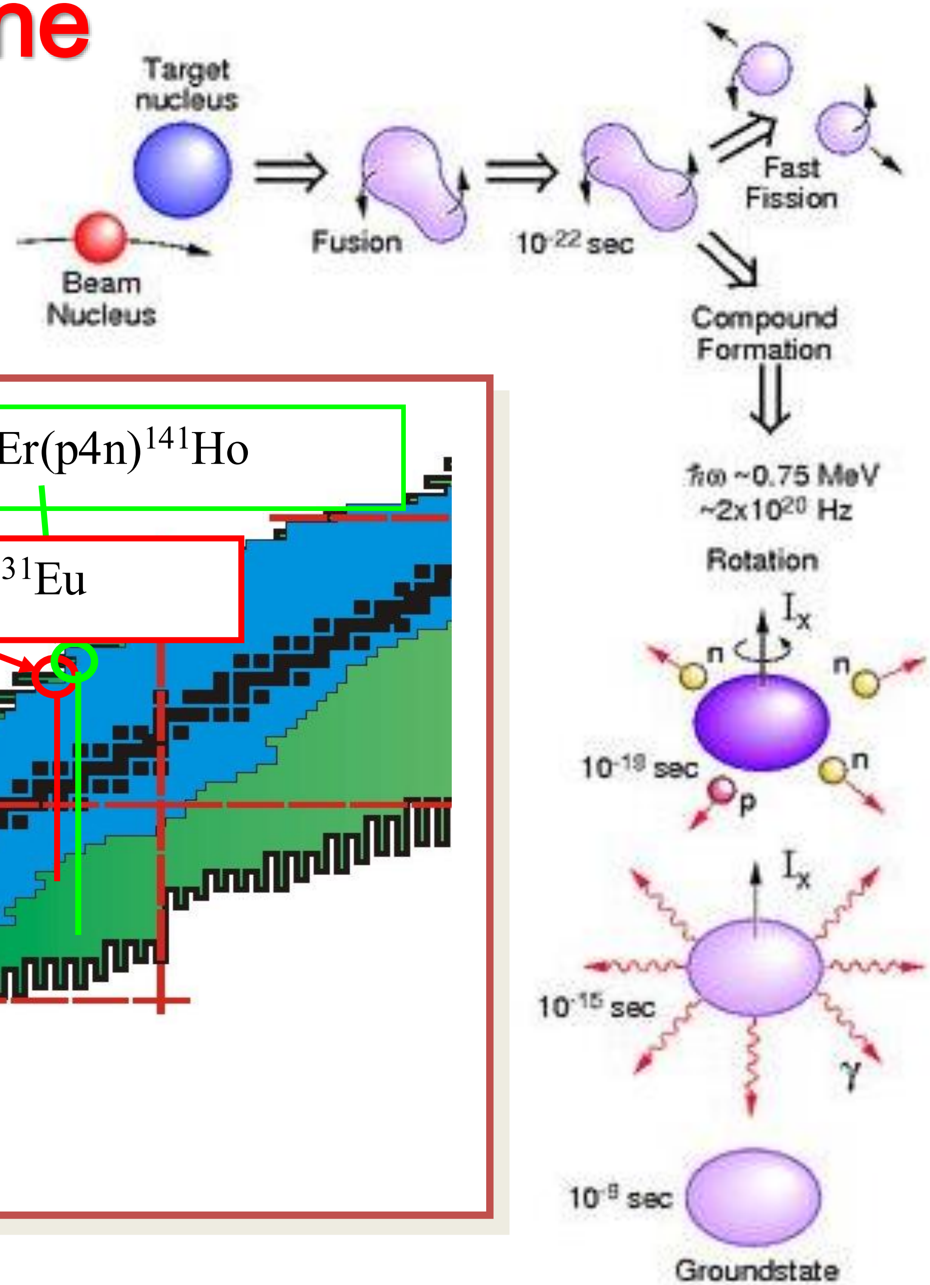
- peripheral elastic and quasi-elastic (QE) collisions
- semi-peripheral deep-inelastic collisions (DIT) collisions
- incomplete (ICF) and complete (CF) fusion in central collisions
- pre-equilibrium emision typically preceding ICF/CF and DIT

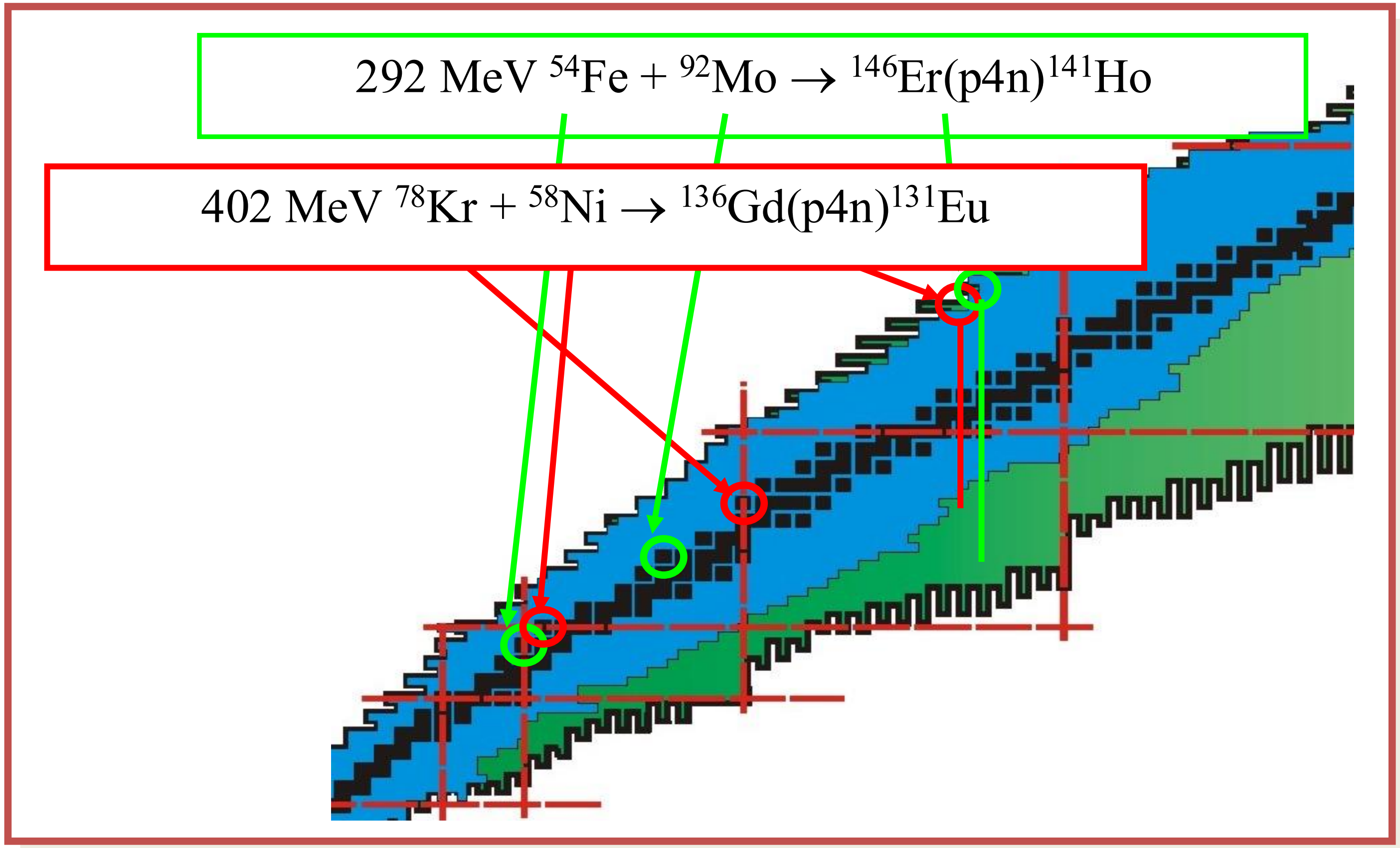
G. R. Satchler. Introduction to Nuclear Reactions. The Macmillan press LTD, 1980.

Reazioni di Produzione

Fusion

(Proj. Energy: Few MeV/A)





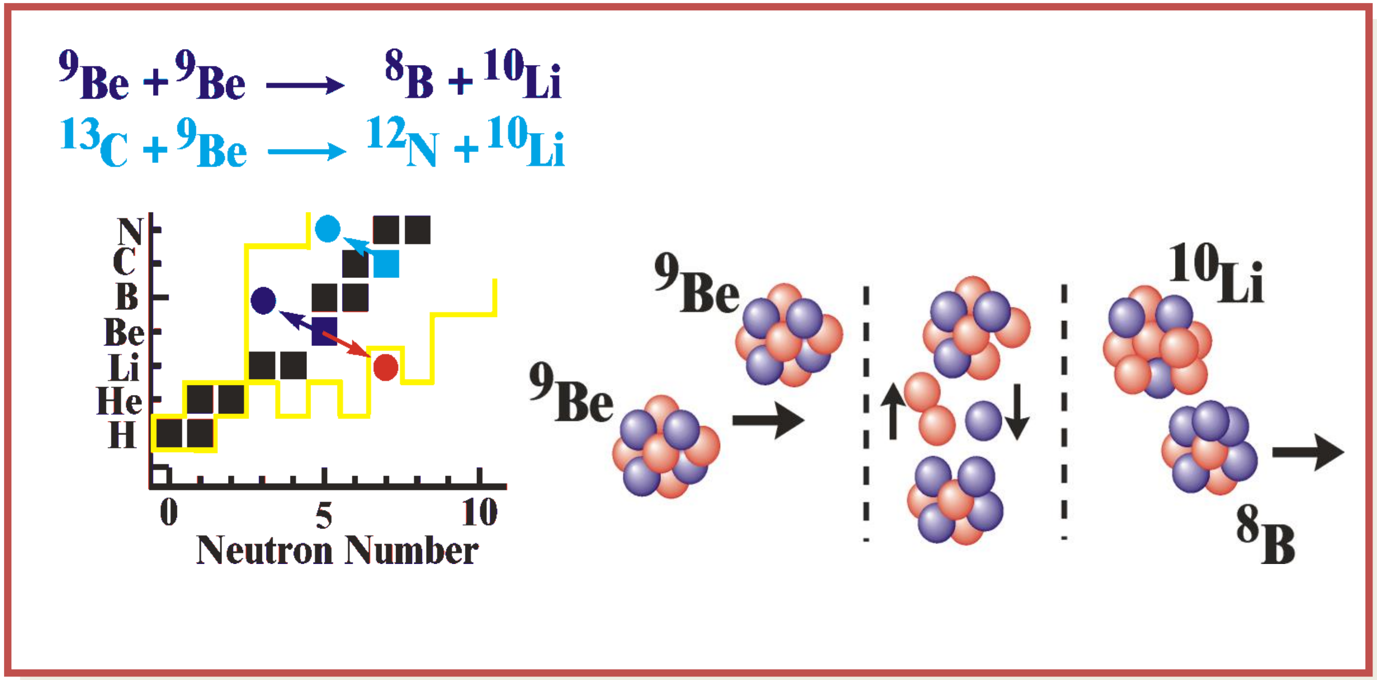
A.A. Sonzogni *et al.,* Phys. Rev. Lett. **83** 1116 (1999)
D. Seweryniak *et al.,* Phys. Rev. Lett. **86** 1458 (2001)

Efficient mechanism to reach proton-rich nuclei

Reazioni di Produzione

Transfer

(Proj. Energy: Few MeV/A)



In generale:

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

Efficient mechanism to move into neutron-rich regions

Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Neutron-rich nuclei produced at zero degrees in damped collisions induced by a beam of ^{18}O on a ^{238}U target

I. Stefan[a,*], B. Fornal[b], S. Leoni[c,d], F. Azaiez[a,1], C. Portail[a], J.C. Thomas[e], A.V. Karpov[i], D. Ackermann[e], P. Bednarczyk[b], Y. Blumenfeld[a], S. Calinescu[h], A. Chbihi[e], M. Ciemala[b],

Cross sections and corresponding momentum distributions have been measured for the first time at zero degrees for the exotic nuclei obtained from a beam of ^{18}O at 8.5 MeV/A impinging on a 1 mg/cm^2 ^{238}U target. Sizable cross sections were found for the production of exotic species arising from the neutron transfer and proton removal from the projectile. Comparisons of experimental results with calculations based on deep-inelastic reaction models, taking into account the particle evaporation process, indicate that zero degree is a scattering angle at which the differential reaction cross section for production of exotic nuclei is at its maximum. This result is important in view of the new generation of zero degrees spectrometers under construction, such as the S3 separator at GANIL, for example.

^{18}O at 8.5 MeV/A impinging on a 1 mg/cm^2 ^{238}U

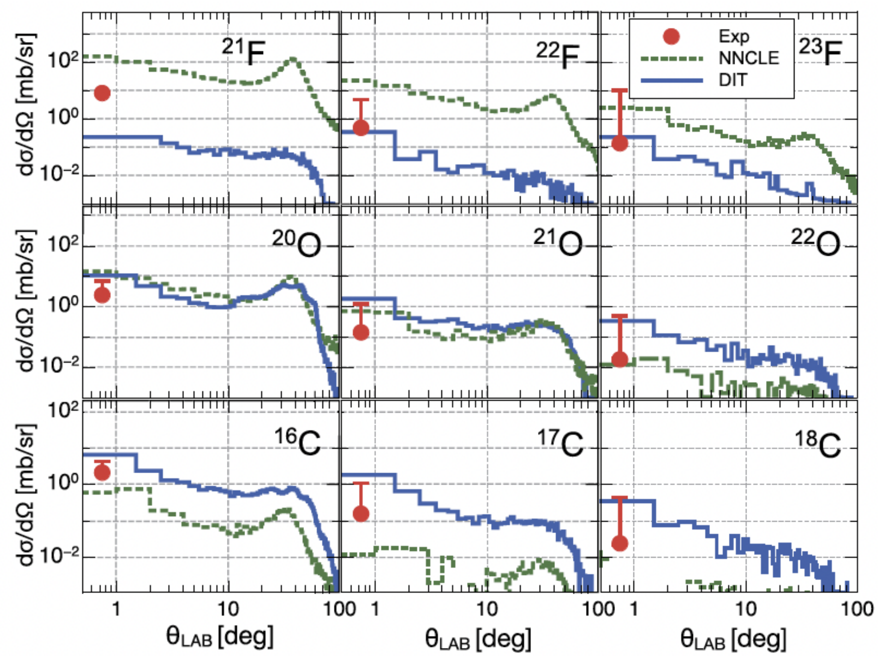


Fig. 3. (Color online) Comparison between the data (red) and the results of calculations for selected nuclei. The calculated $d\sigma/d\Omega$ cross sections as a function of angle are given in green for the NNCLE + NRV model and in blue for DIT + Gemini++ approach (see text for details).

PHYSICAL REVIEW C **89**, 054608 (2014)

Formation of light exotic nuclei in low-energy multinucleon transfer reactions

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[2] *The Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[3] *Dipartimento di Fisica, University of Milano, Milano, Italy*
[4] *Frankfurt Institute for Advanced Studies, J.W. Goethe-Universität, Frankfurt, Germany*
(Received 13 March 2014; published 9 May 2014)

Low-energy multinucleon transfer reactions are shown to comprise a very effective tool for the production and spectroscopic study of light exotic nuclei. The corresponding cross sections are found to be significantly larger as compared with high-energy fragmentation reactions. Several optimal reactions for the production of extremely neutron-rich isotopes of elements with $Z = 6$–14 are proposed.

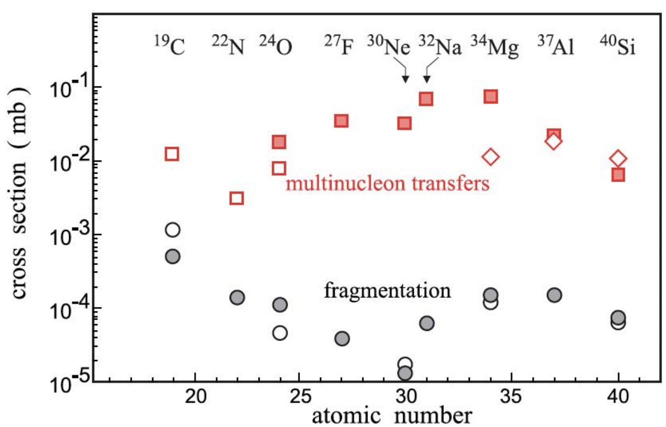


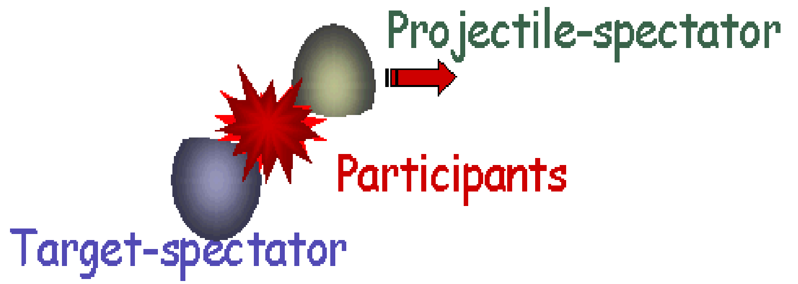
FIG. 8. (Color online) Cross sections for the formation of light neutron-rich nuclei in low-energy collisions of ^{18}O (open rectangles), ^{26}Mg (solid rectangles), and ^{36}S (open diamonds) with ^{238}U target and in fragmentation of 128 *A* MeV ^{48}Ca on ^{181}Ta target [5] (solid circles) and 345 *A* MeV ^{48}Ca on ^{9}Be target [3] (open circles).

As can be seen from the obtained results, the cross sections for the formation of light neutron-rich nuclei in low-energy damped collisions of light heavy ions with heavy targets are significantly larger than the corresponding yields of these nuclei in high-energy fragmentation processes.

In Fig. 8 formation cross sections of several neutron-rich nuclei (such as ^{19}C, ^{24}O, ^{30}Ne, etc.) are compared for both the processes. The yields of these nuclei in the low-energy multinucleon transfer reactions are higher by about 2 orders of magnitude as compared with fragmentation reactions. Note that the intensity of low-energy primary beams of such projectiles as ^{18}O, ^{26}Mg, and others can also be much higher than the intensity of high-energy beams used in the fragmentation reactions. Both factors make low-energy damped collisions of light heavy ions quite attractive for the production and study of light exotic nuclei just at presently available experimental facilities.

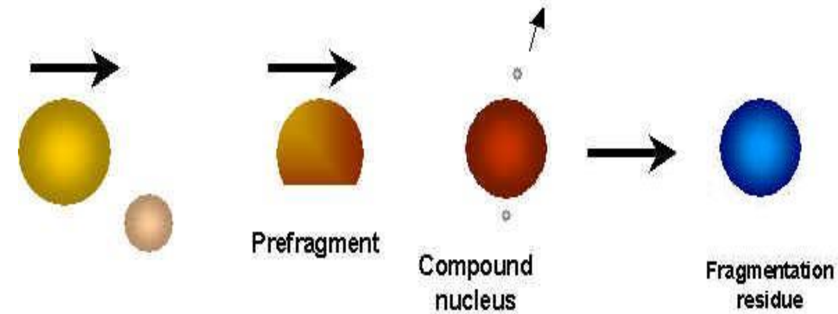
Reazioni di Produzione

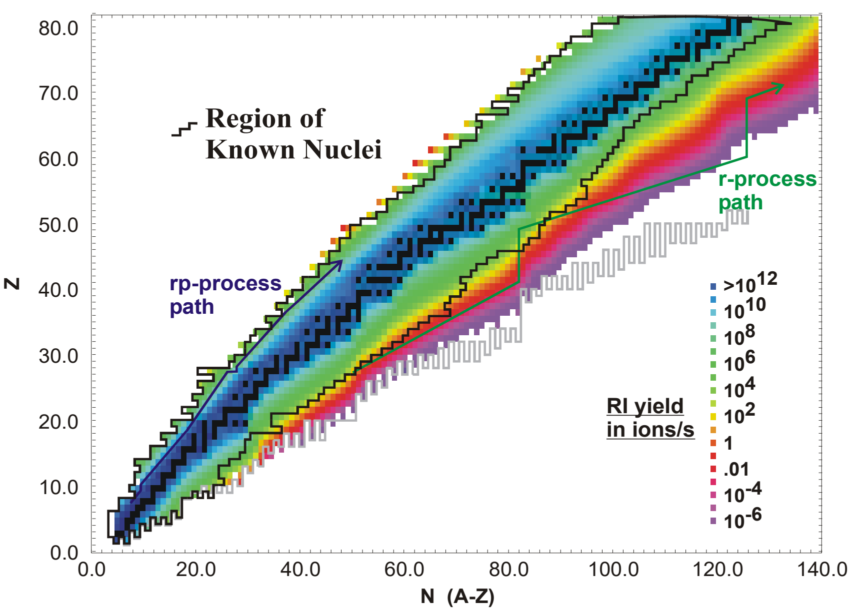
Projectile Fragmentation



(Proj. Energy: > 100 MeV/A)

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





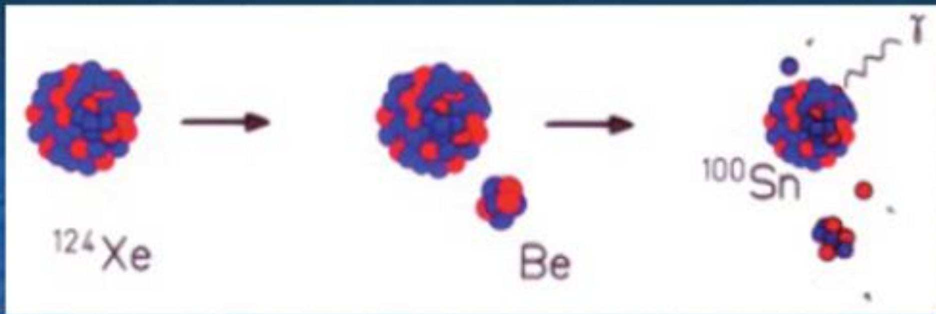
Peripheral Collision - rather than central.

Mechanism Stages - three stages:

- Abrasion: The outer parts of the projectile and target "scrape" or "abrade" each other, removing a portion of the nucleus.
- Multifragmentation: The remaining projectile spectator (projectile-like fragment) is highly excited and can break into several smaller pieces.
- Evaporation/Decay: The excited residues decay by emitting neutrons, protons, or alpha particles. *very difficult predictions of cross sections!!!*

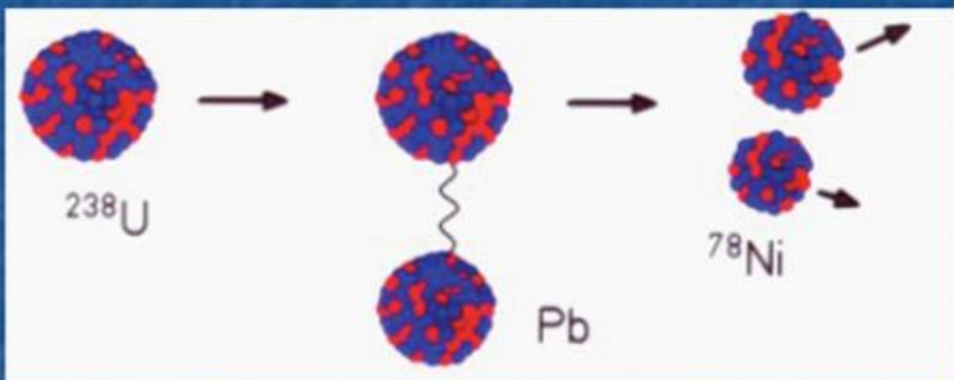
Forward Focusing: produced fragments are focused in the forward direction, following the high velocity of the original beam, making them easy to separate and isolate using in-flight magnetic separators.

Heavy-ion induced reactions



Fragmentation

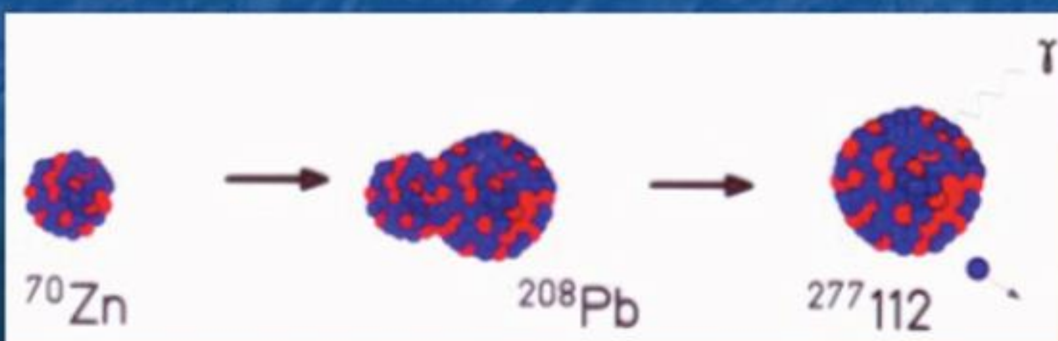
(Proj. Energy: ≥ 100 MeV/A)



Coulomb dissociation

(Proj. Energy: ≥ 100 MeV/A)

(proj. excited in Coulomb field to unbound states; equivalent to absorption of virtual photons)



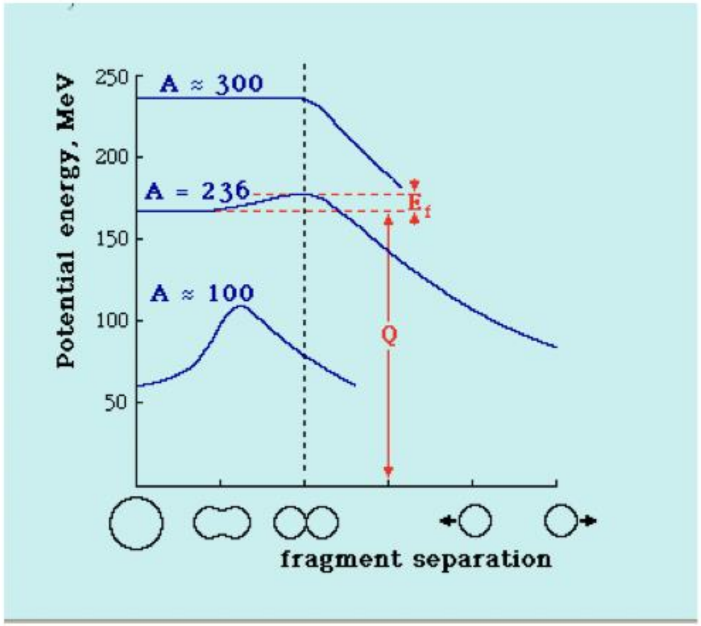
Fusion

(and Transfer)

(Proj. Energy: few MeV/A)

Reazioni di Produzione

Induced Fission



- For inducing fission, one has to provide energy to the nucleus, so that its parts can overcome the fission barrier, or form a compound nucleus where the barrier is diminished or eliminated.
- In principle on can induce fission by :

-photofission

γ+ (Z,A) ➔ (Z,A)* ➔ (Z_1,A_1) + (Z_2,A_2) +neutrons

-proton induced fission

p+ (Z,A) ➔p+ (Z,A)* ➔ (Z_1,A_1) + (Z_2,A_2)+neutrons

-neutron induced fission

n+ (Z,A) ➔ (Z,A+1)* ➔ (Z_1,A_1) + (Z_2,A_2)+neutrons

Nuclide	Half-life	Fission prob. per decay (%)	Neutrons per fission
^{235}U	7.04×10^8 years	7.0×10^{-9} %	1.86
^{238}U	4.47×10^9 years	5.4×10^{-5} %	2.07

Reazioni di Produzione

Induced Fission

with photons

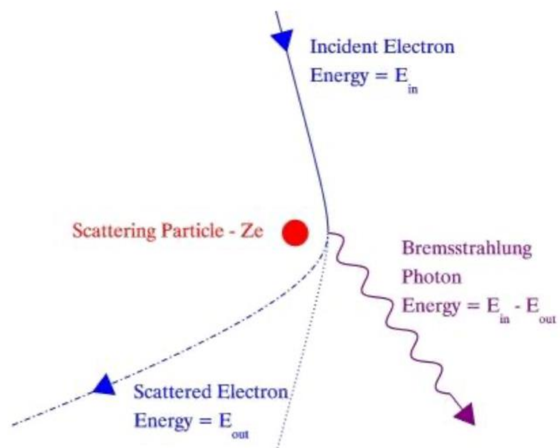
high-energy photons (with continuum spectrum)
can be produced by electrons beams
slowing down in a thick material
Bremsstrahlung process

FAST electrons can loose energy by
- Ionization/collisions (Bethe-Block)
- Radiation (bremsstrahlung)

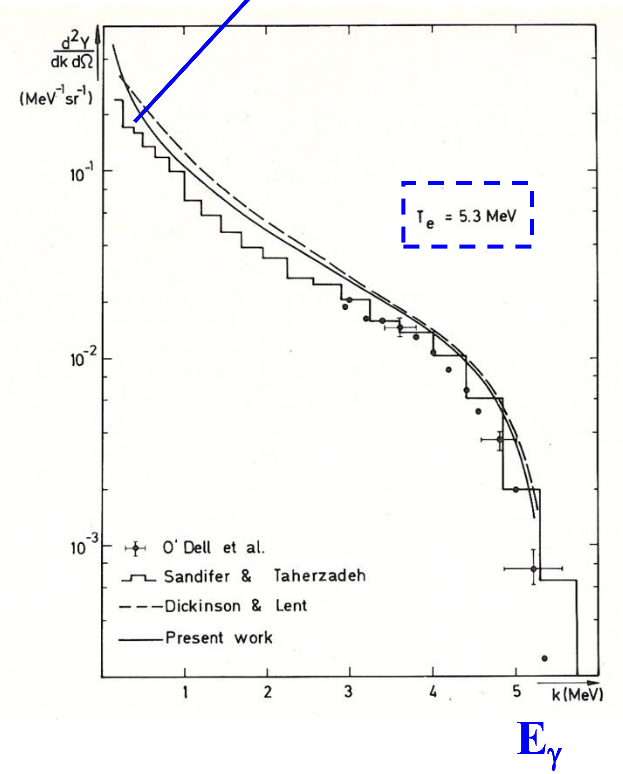
$$-\left(\frac{dE}{dx}\right)_r \approx \frac{\rho E Z(Z+1)e^4}{137 m_e^2 c^4}\left(4\ln\frac{2E}{m_e c^2}-\frac{4}{3}\right)$$

$$\approx E\rho Z^2 \rightarrow$$

large radiation energy loss for energetic electrons in heavy materials



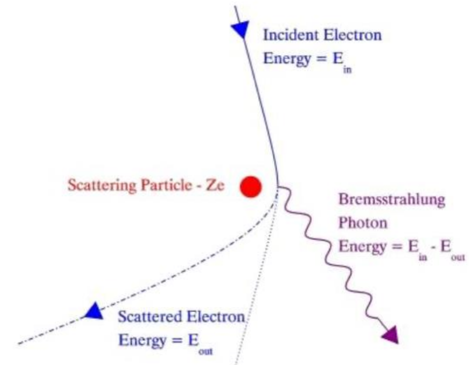
bremsstrahlung photon energy
is quite **small**
⇒ it is mostly reabsorbed
close to its point of origin



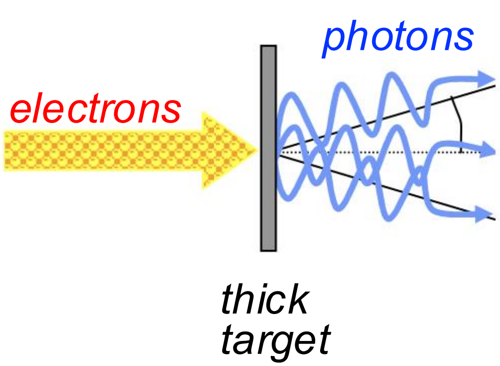
Reazioni di Produzione

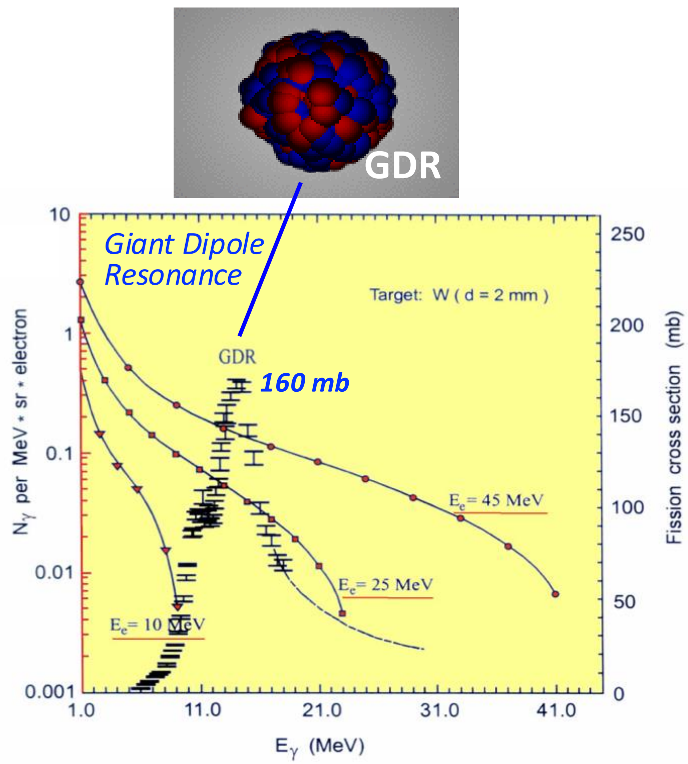
Induced Fission

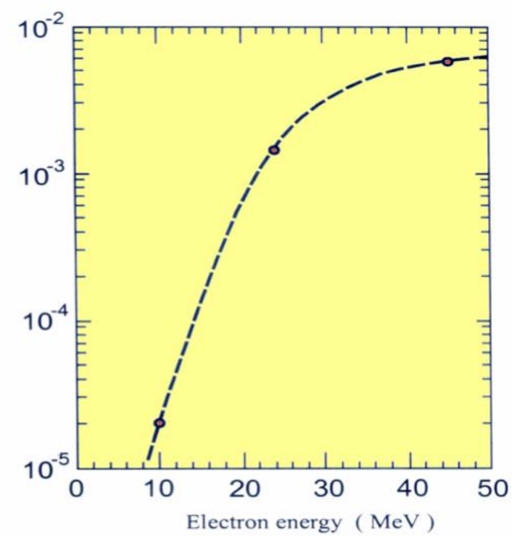
with photons



high-energy photons (with continuum spectrum)
can be produced by electrons beams
slowing down in a thick material
Bremsstralhung process

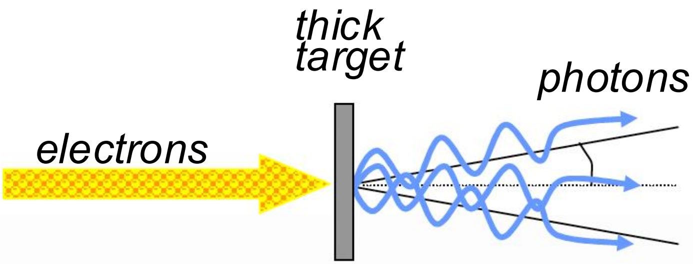






Production of Rare Nuclei at ALTO (IJCLAB in Orsay)

Similar facility under construction at IFIN-HH (Romania)

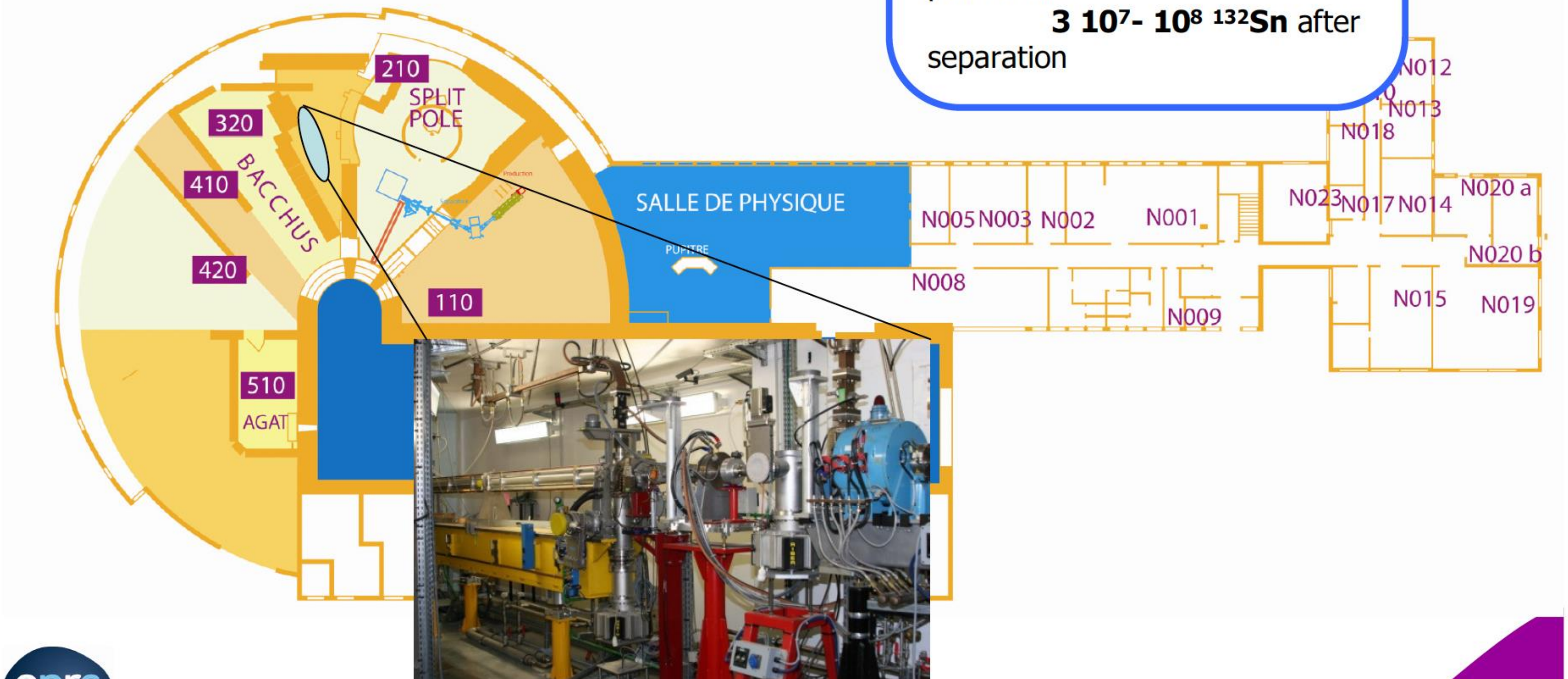


ALTO LINAC (formerly 1st section of the LEP injector) :
10μA, 50 MeV electrons

factor 100 in comparison with deuterons

10^{11}-4 10^{11} fissions per second

3 10^{7}- 10^{8} ^{132}Sn after separation



The ALTO production

M. Lebois, M. Cheikh Mahmed

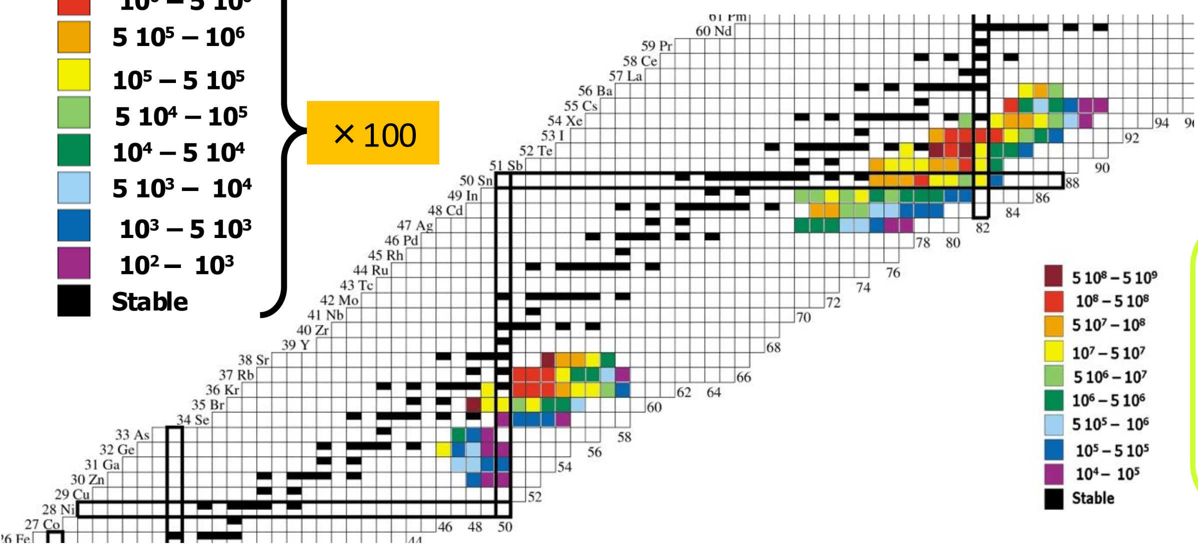
Measured productions yields
at the detection point at PARRNe

June 2006

Production /s/100nA

- $5\ 10^6 - 5\ 10^7$
- $10^6 - 5\ 10^6$
- $5\ 10^5 - 10^6$
- $10^5 - 5\ 10^5$
- $5\ 10^4 - 10^5$
- $10^4 - 5\ 10^4$
- $5\ 10^3 - 10^4$
- $10^3 - 5\ 10^3$
- $10^2 - 10^3$
- Stable

× 100



Photofission for the production of radioactive beams: Experimental data from an on-line measurement

The pioneering photo-fission experiment at CERN

F. Ibrahim[1,a], J. Obert[1], O. Bajeat[1], J.M. Buhour[1], D. Carminati[2], F. Clapier[1], C. Donzaud[1], M. Ducourtieux[1], J.M. Dufour[1], S. Essabaa[1], S. Galès[1], D. Guillemaud-Mueller[1], F. Hosni[1], O. Hubert[1], A. Joinet[2], U. Köster[2], C. Lau[2], H. Lefort[1], G. Le Scornet[2], J. Lettry[2], A.C. Mueller[1], M. Mirea[3], N. Pauwels[1], O. Perru[1], J.C. Potier[1], J. Proust[1], F. Pougheon[1], H. Ravn[2], L. Rinolfi[2], G. Rossat[2], H. Safa[4], M.G. Saint Laurent[5], M. Santana-Leitner[2], O. Sorlin[1], and D. Verney[1]

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4 SEA, CEA, Saclay, France
5 GANIL, BP55027, 14076 Caen Cedex, France

Received: 20 July 2001 / Revised version: 16 May 2002 /
Published online: 19 November 2002 – © Società Italiana di Fisica / Springer-Verlag 2002
Communicated by D. Guerreau

Abstract. A PARRNe 1 experiment (Production d'Atomes Radioactifs Riches en Neutrons) aimed at the production of neutron-rich radioactive noble gases produced by photofission has been performed at CERN. The LEP Pre-Injector (LPI) has been used to deliver a 50 MeV electron beam. The results obtained show clearly that the use of an electron beam to produce neutron-rich fission fragments for futur RNB facilities is an option that should not be neglected.

PACS. 25.85.Jg Photofission – 29.25.Rm Sources of radioactive nuclei – 25.20.-x Photonuclear reactions

Eur. Phys. J. A **15**, 357–360 (2002)
DOI 10.1140/epja/i2001-10222-0

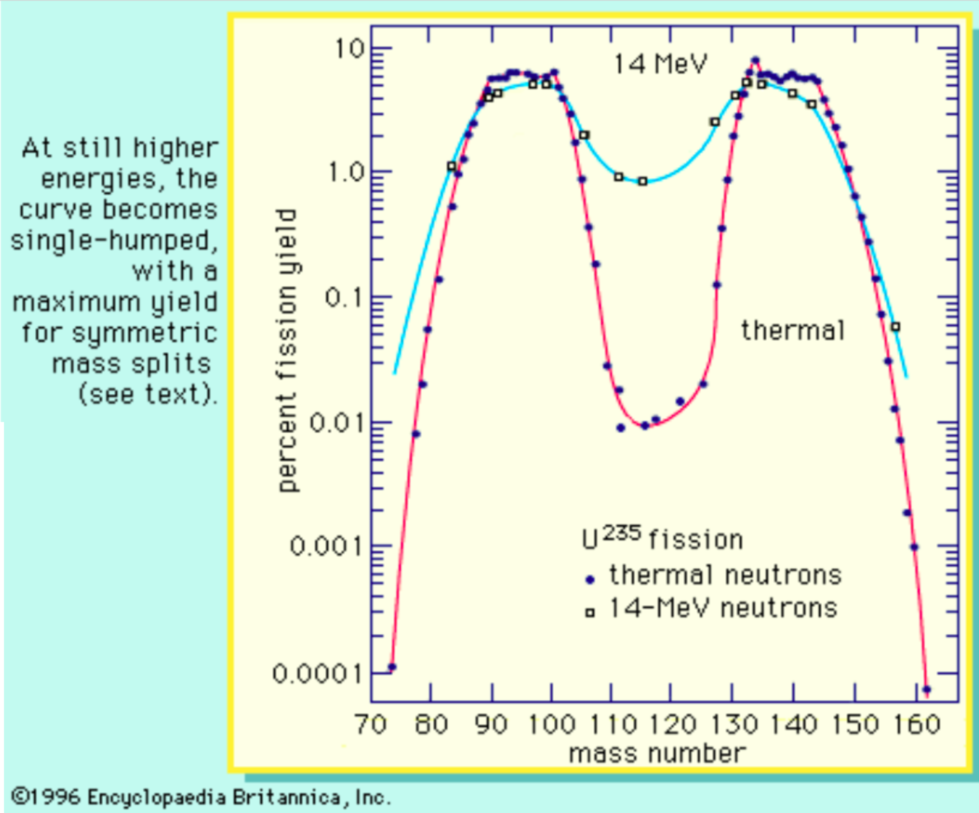
Hot plasma ion source
100nA electrons
50 MeV
Uranium Carbide target (UCx)
140 mm thick
10^9 fissons/s inside the target

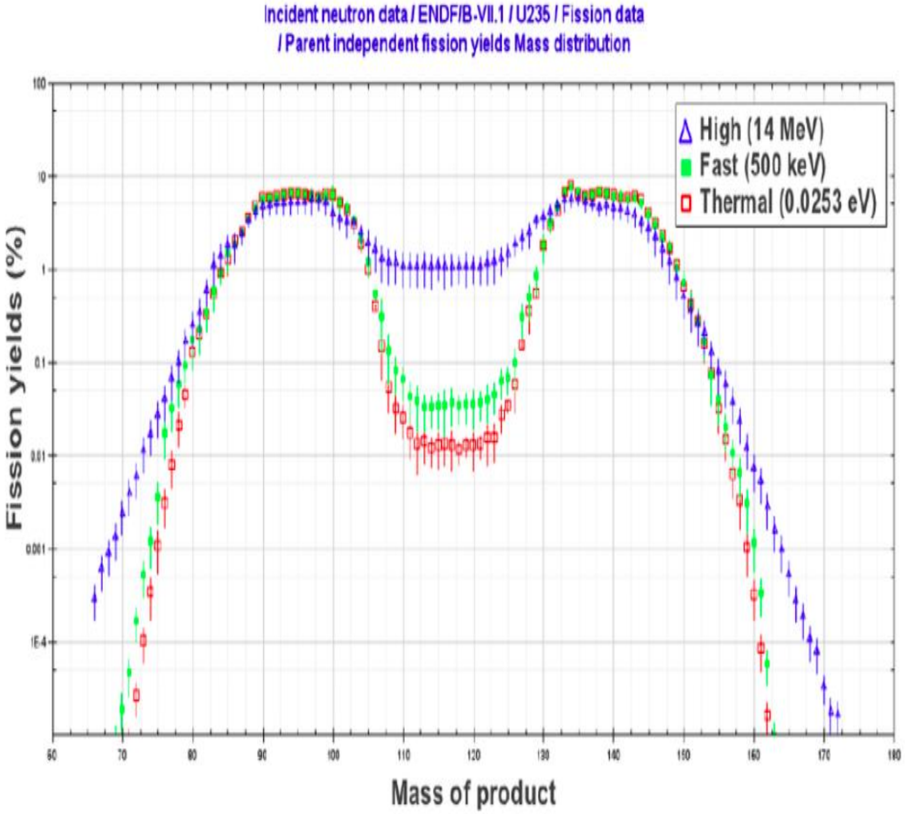
nominal intensity:
10 μA ⇒~ 10^{11} fissions/s

Reazioni di Produzione

Induced Fission

with neutrons





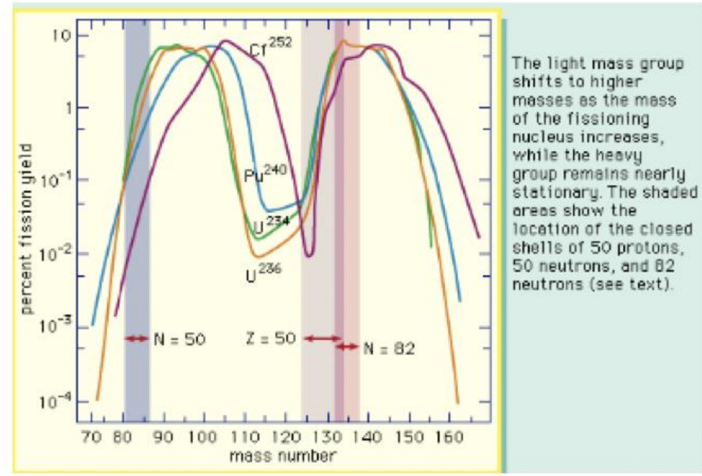
Carefull:
fission yields and not absolute cross sections !!!

$\sigma(n_{th},fission) = 585\ b\ (^{235}U)$

Reazioni di Produzione

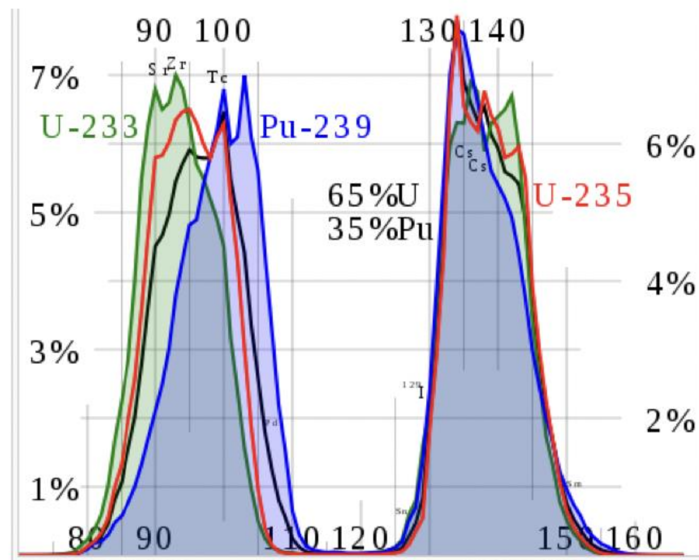
Induced Fission

with neutrons



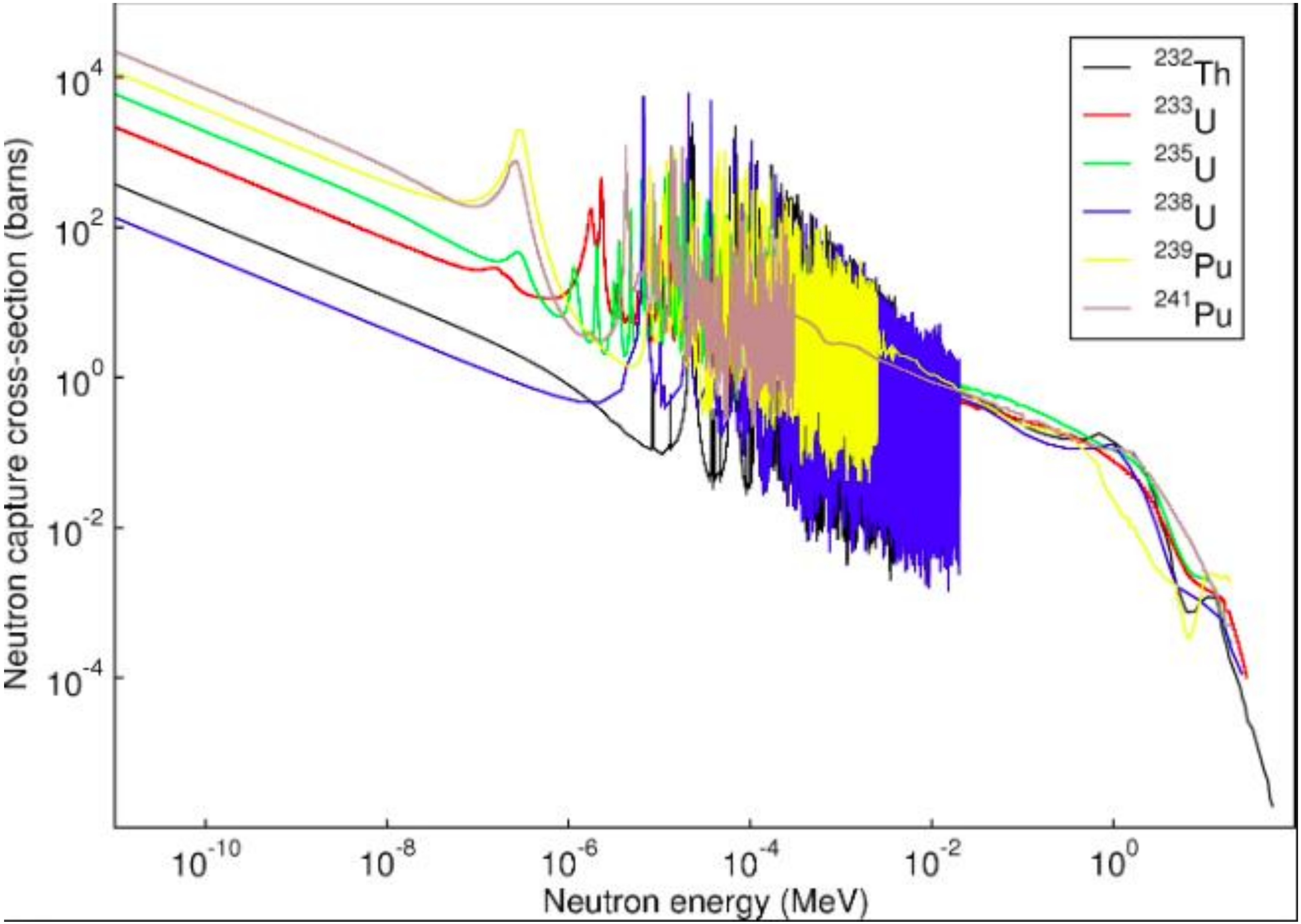
Fission fragments and Fission products

- ***Fission fragments** have a double bell distribution as a function of A, which depends on the type of fissile target and on the neutron (or proton, etcc…) energy.*
- *Fission fragments are unstable and decay towards stable nuclei via beta decays, leading to the **fission products**.*
- ***50% of fission products have decay times less than one year**, the rest has lifetimes that can be as long as million years*



Fission product yields by mass for thermal neutron fission of U-235, Pu-239, a combination of the two typical of current nuclear power reactors, and U-233 used in the thorium cycle

Neutron Induced Fission – CROSS SECTIONS !!!



Reazioni di Produzione

Induced Fission

with neutrons

La Rivista del Nuovo Cimento
https://doi.org/10.1007/s40766-022-00033-2

REVIEW PAPER

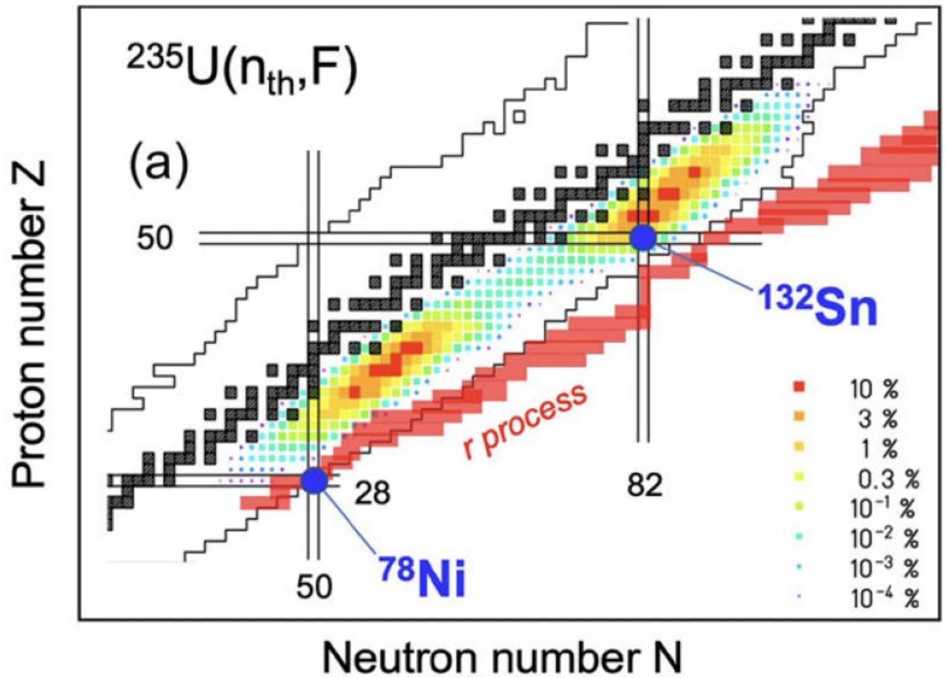
Check for updates

Gamma-ray spectroscopy of fission fragments with state-of-the-art techniques

S. Leoni[1,2] · C. Michelagnoli[3] · J. N. Wilson[4]

Received: 21 December 2021 / Accepted: 2 March 2022

Abstract
The paper reviews recent developments in γ-ray spectroscopy of the neutron-rich fragments produced in nuclear fission. This subject has been an intensive area of study spanning more than five decades. Here we highlight key results and describe the evolution of the associated experimental techniques since the last review papers in 1995 (I. Ahmad and W.R. Phillips, Rep. Prog. Phys. 58(11), 1415 (1995); J. H. Hamilton et al., Prog. Part. Nucl. Phys. 35, 635(1995)). Research themes in nuclear structure will be explored along with the fission reaction mechanism and the links to nuclear astrophysics and applications.

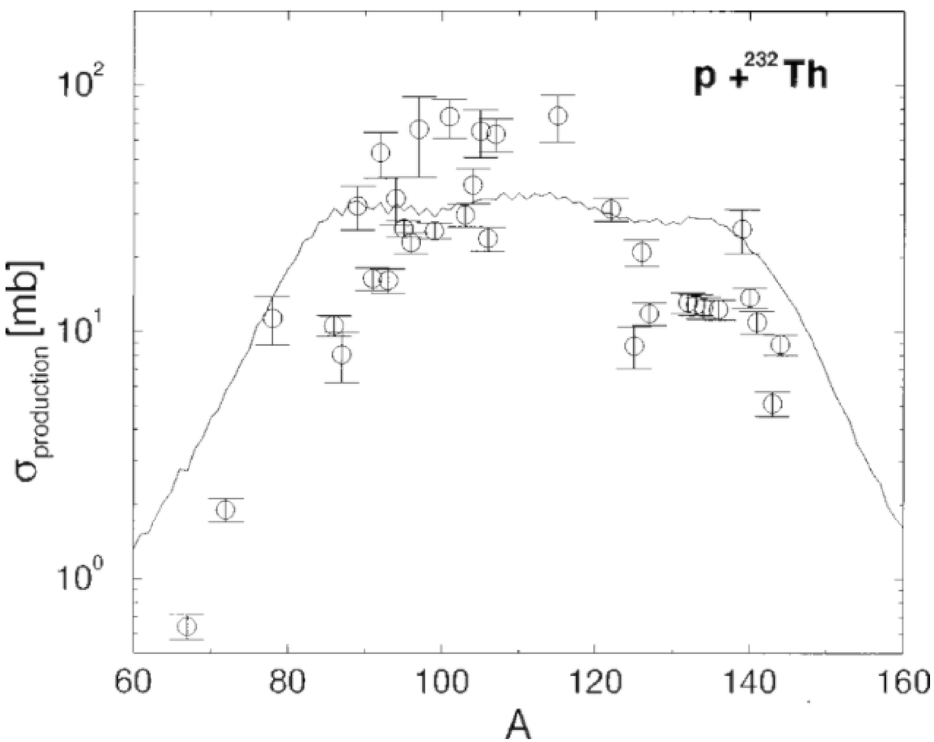


Reazioni di Produzione

Induced Fission

with protons

FIG. 9. Experimental mass yields for 190 MeV proton-induced fission of 232 Th circles. The curve for complete fission yields has been calculated with LAHET.



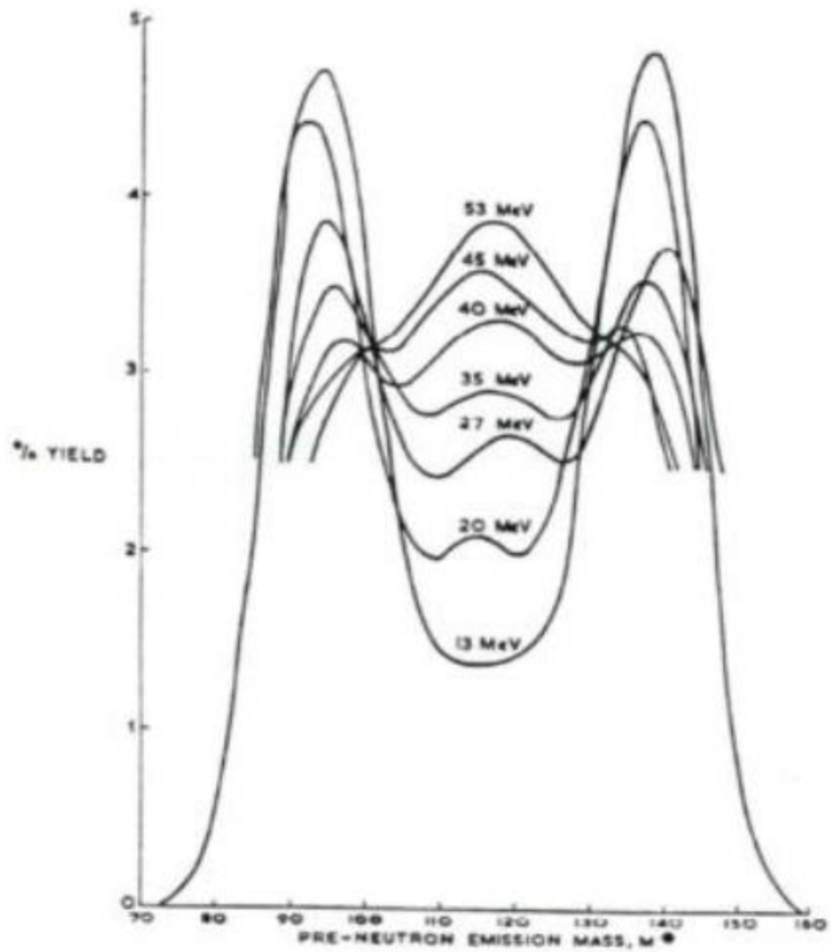
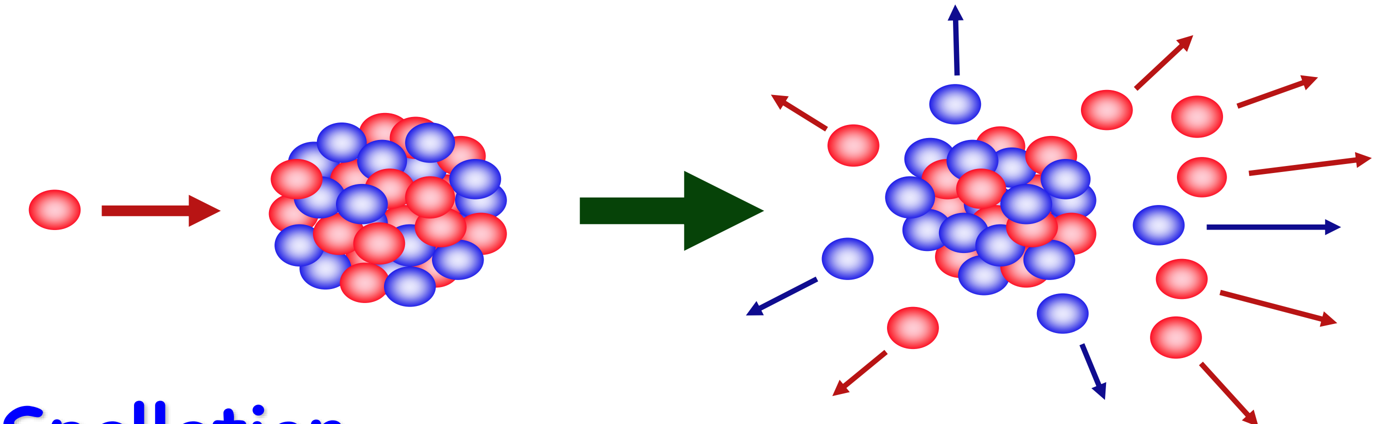


Figure 11-17. Fission mass distributions for ^{232}Th(p, f)

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

High energy projectile (up to GeV)

- ***CERN*** (***protons*** *on U, or other targets, ...) – Nuclear physics and applications*
- ***European Spallation Source*** *(ESS in Lund, Sweden) - mainly material science:* accelerator-based neutron source facility: **neutrons** are liberated from heavy elements (Tungsten) by high energy **protons**. This is intrinsically a much safer process than uranium fission.

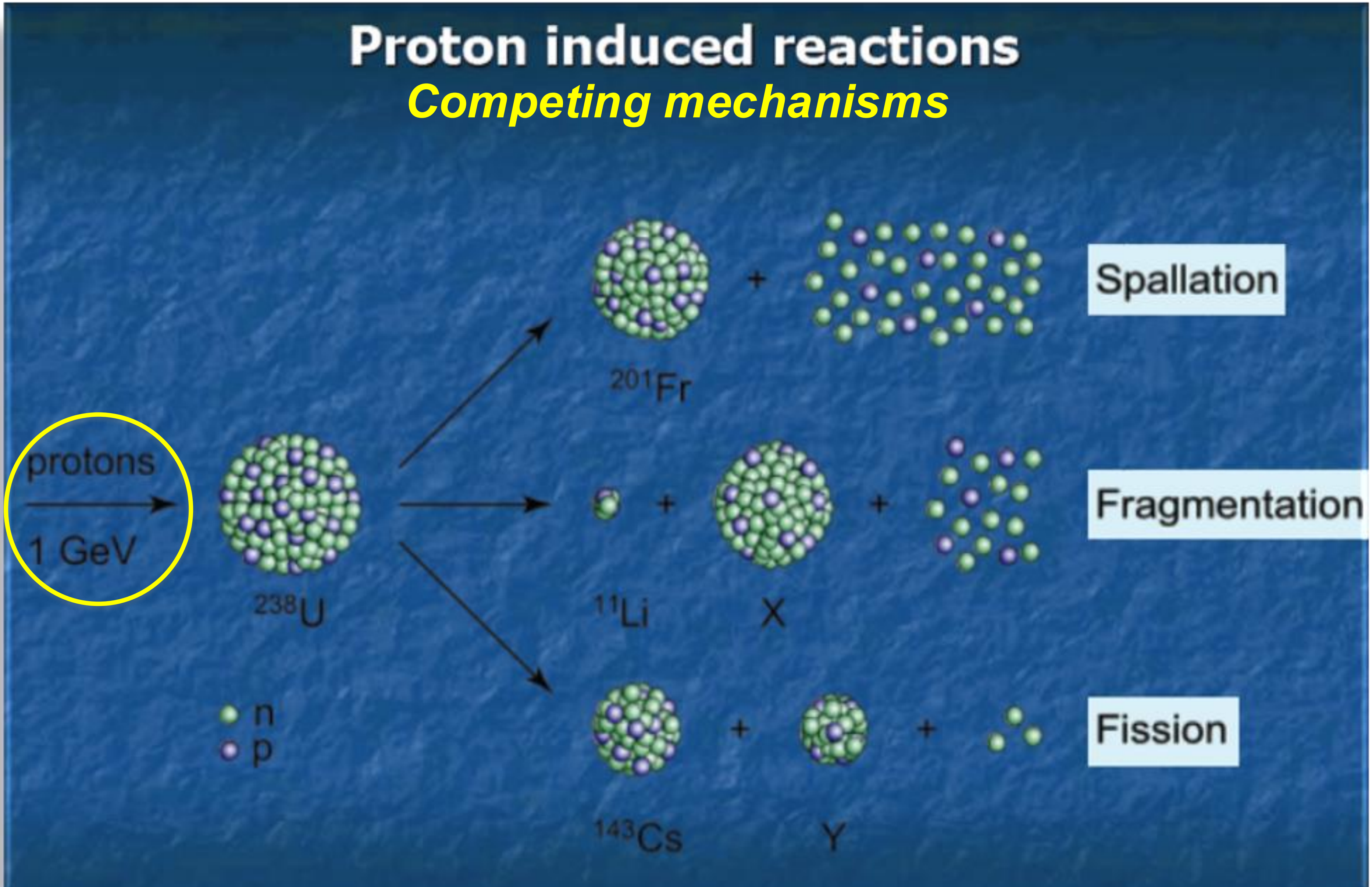
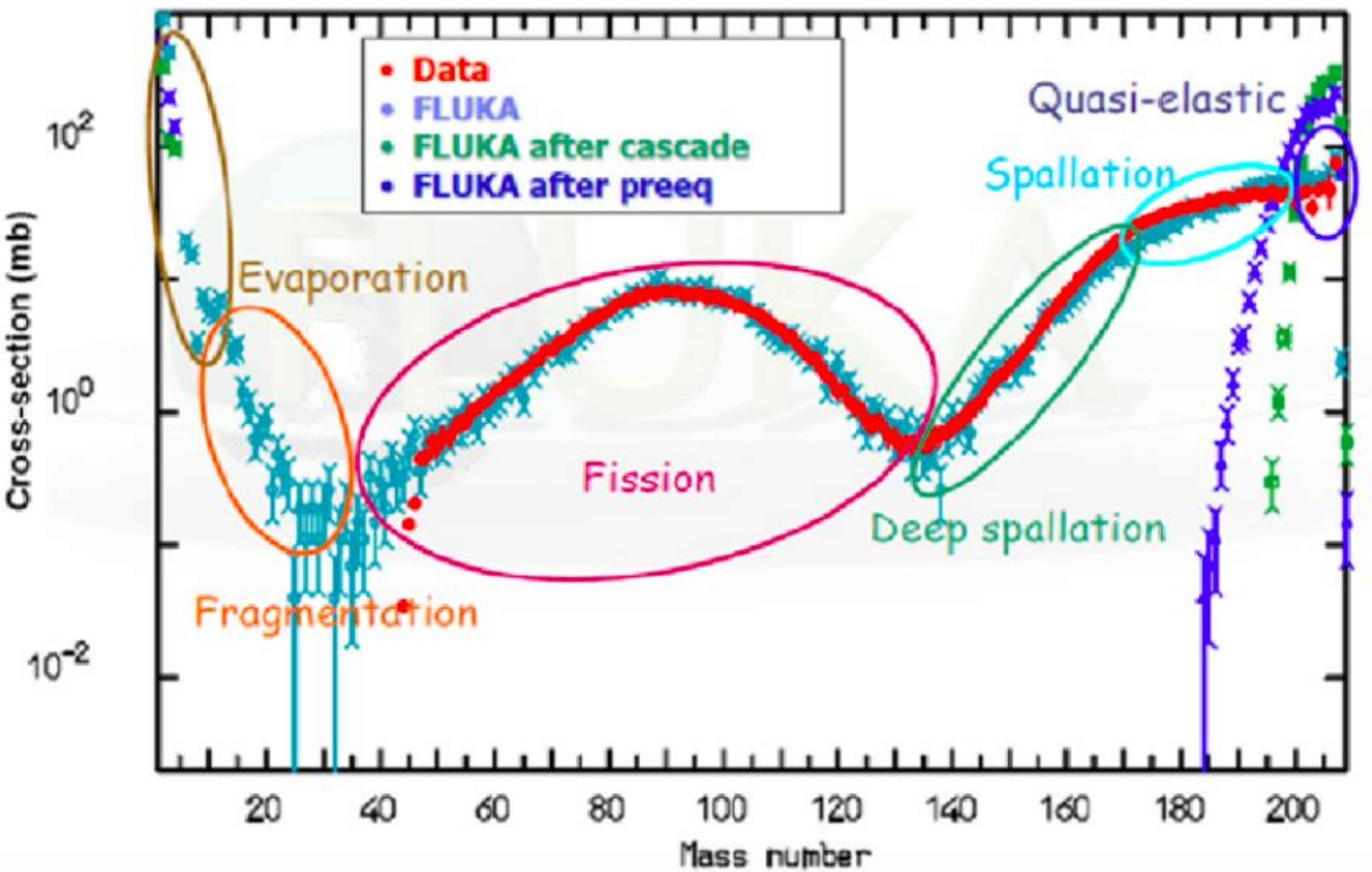

Proton induced reactions
Competing mechanisms
protons
1 GeV
238U
n
p
201Fr
Spallation
11Li
X
Fragmentation
143Cs
Y
Fission

Fig. 3: Mass distribution predicted by FLUKA after bombardment of Pb with 1 GeV protons. The data are taken from Ref. [10]. Image courtesy of A. Ferrari, CERN.

ISOLDE (CERN) Target



ISOLDE (CERN) Target

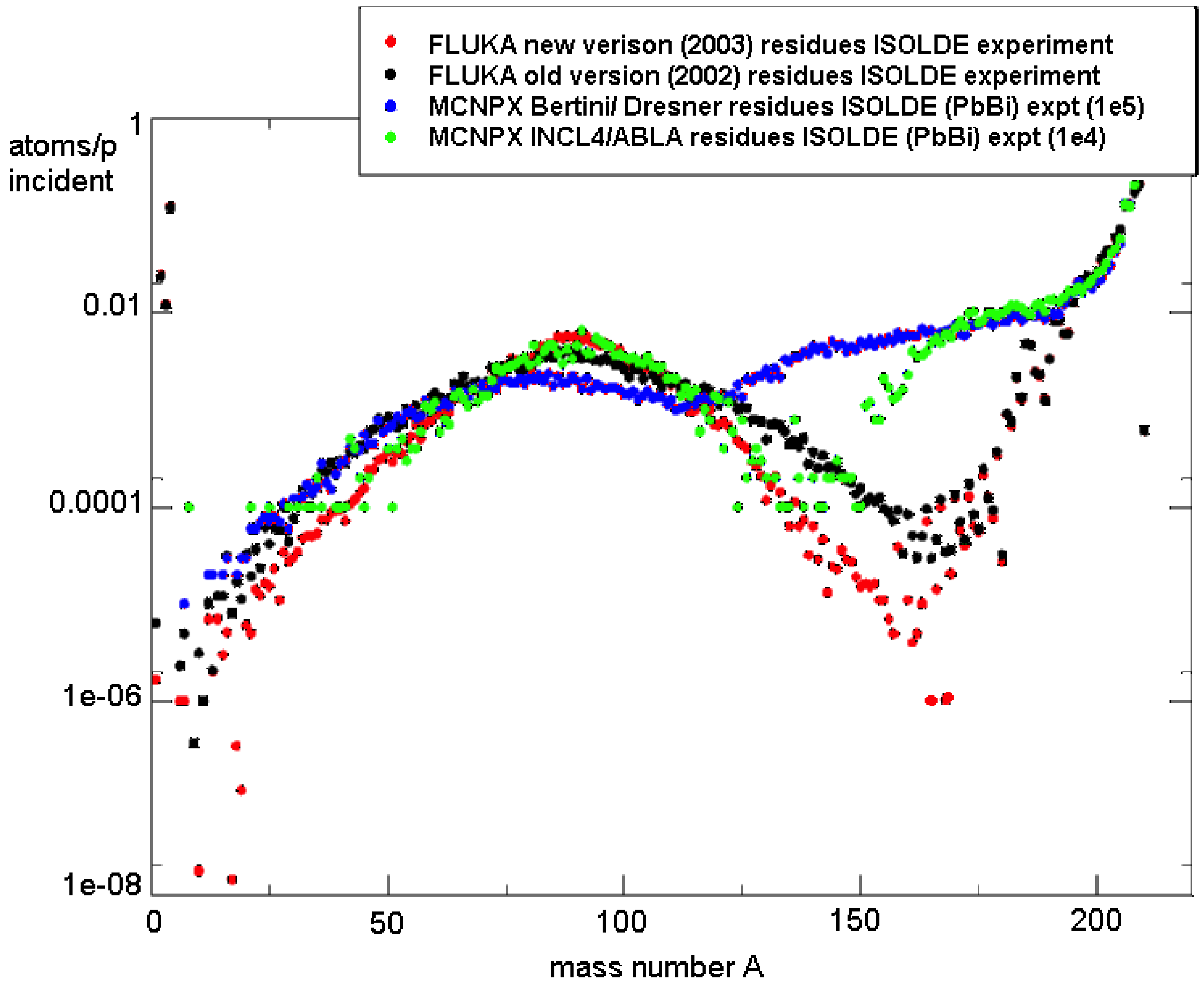
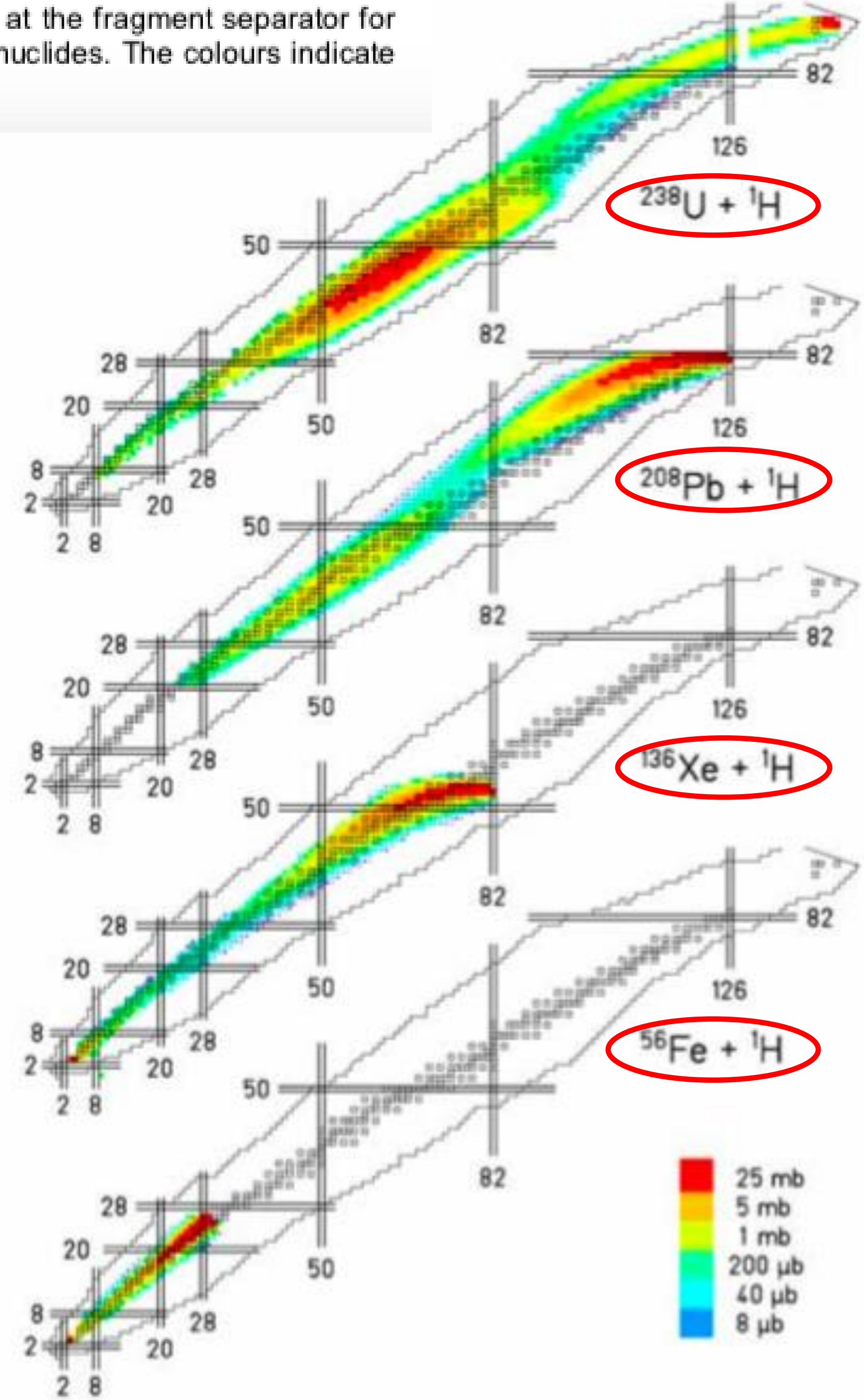


Figure 7. Overview on the nuclide production cross sections measured at the fragment separator for the four systems indicated at the energy of 1 *A* GeV on a chart of the nuclides. The colours indicate the production cross sections as defined in the colour scale.

Spallation/Fragmentation in Inverse Kinematics

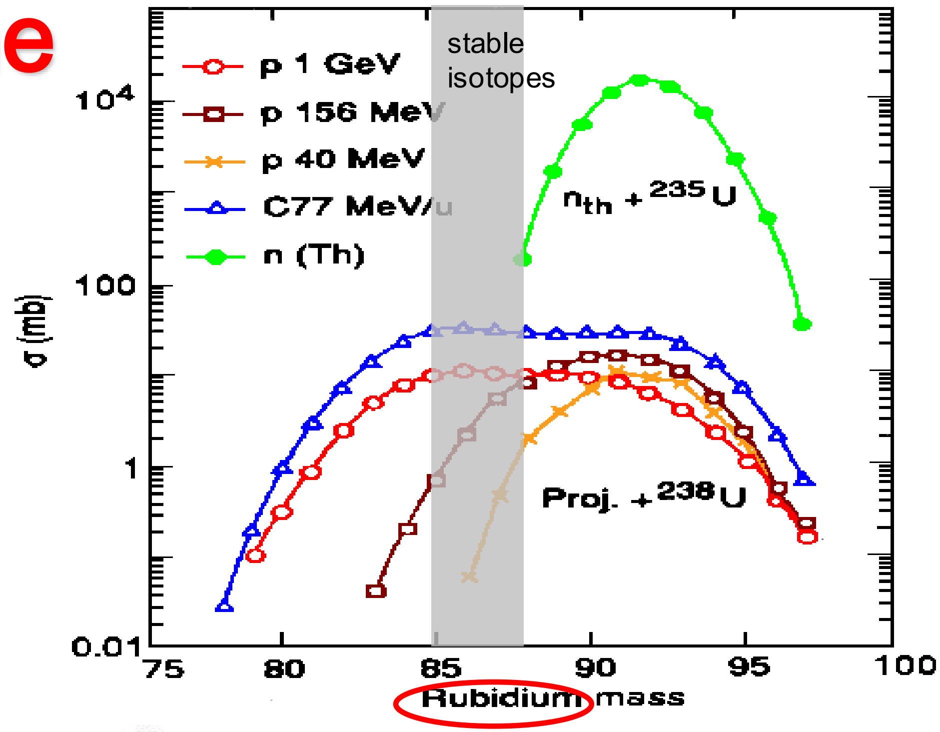
(∽ 1 GeV/A)

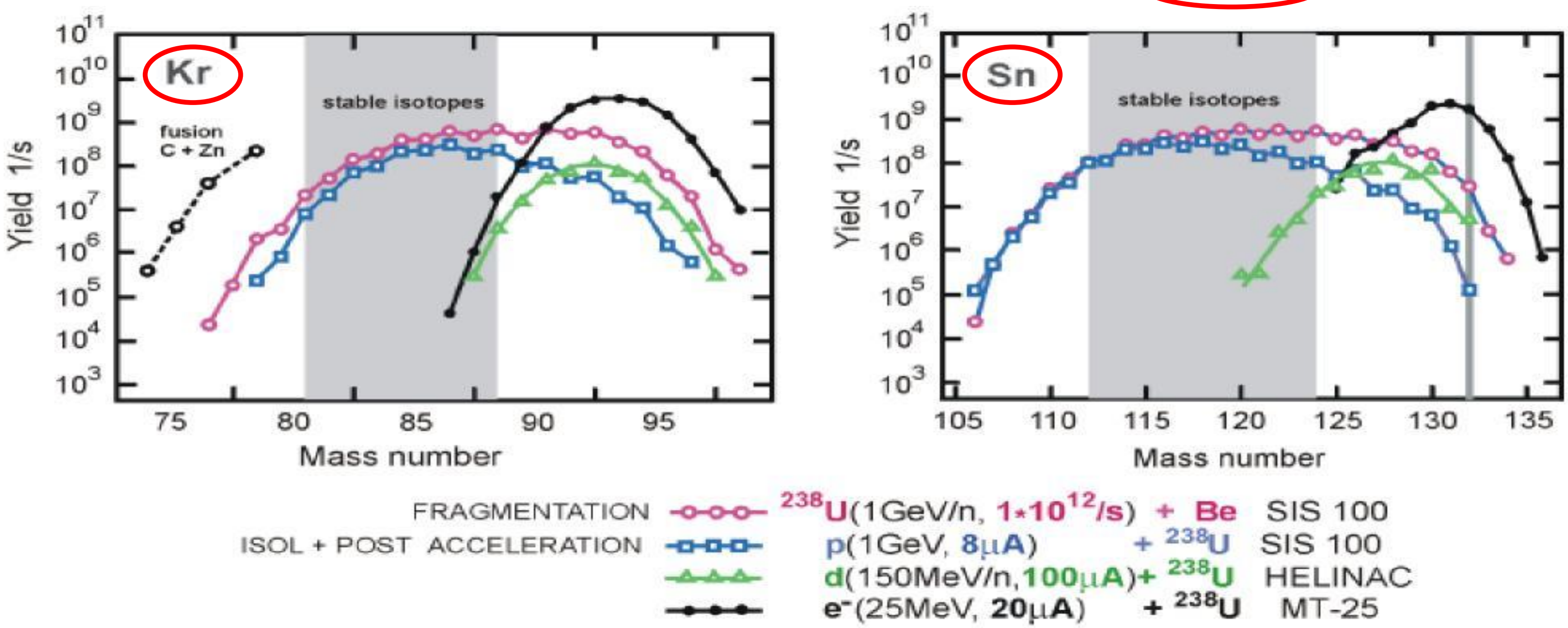
(forward focus reaction products: efficient detection)



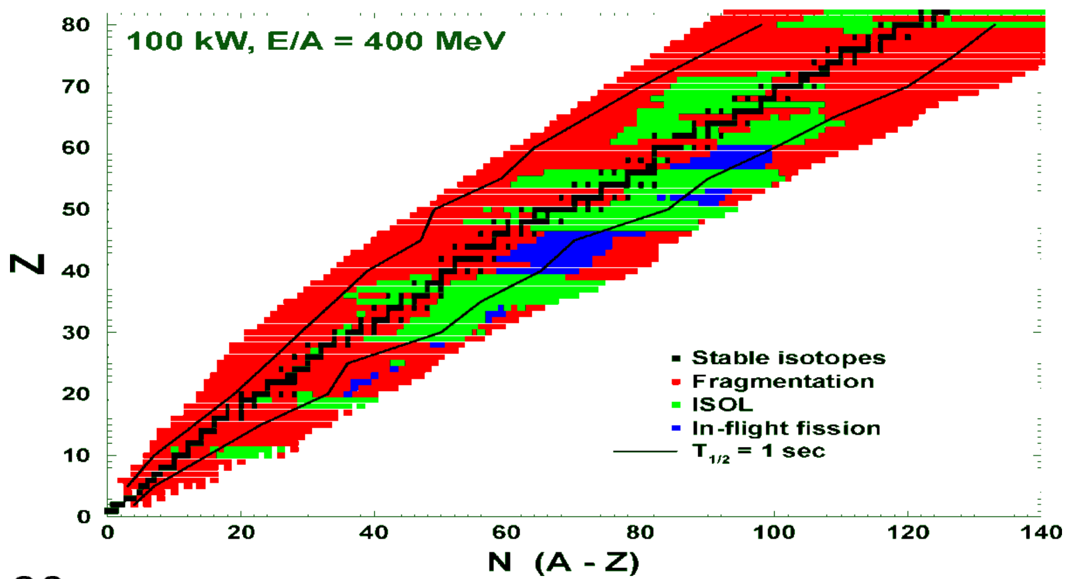
Reazioni di Produzione

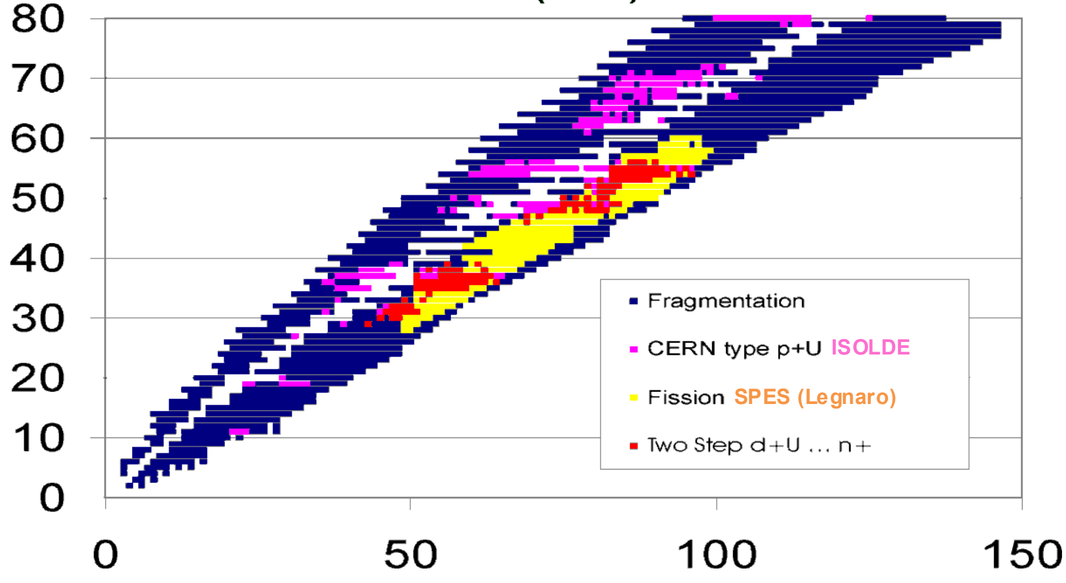
Comparisons





Optimum Reazioni di Produzione





Meccanismi di produzione alternativi e complementari

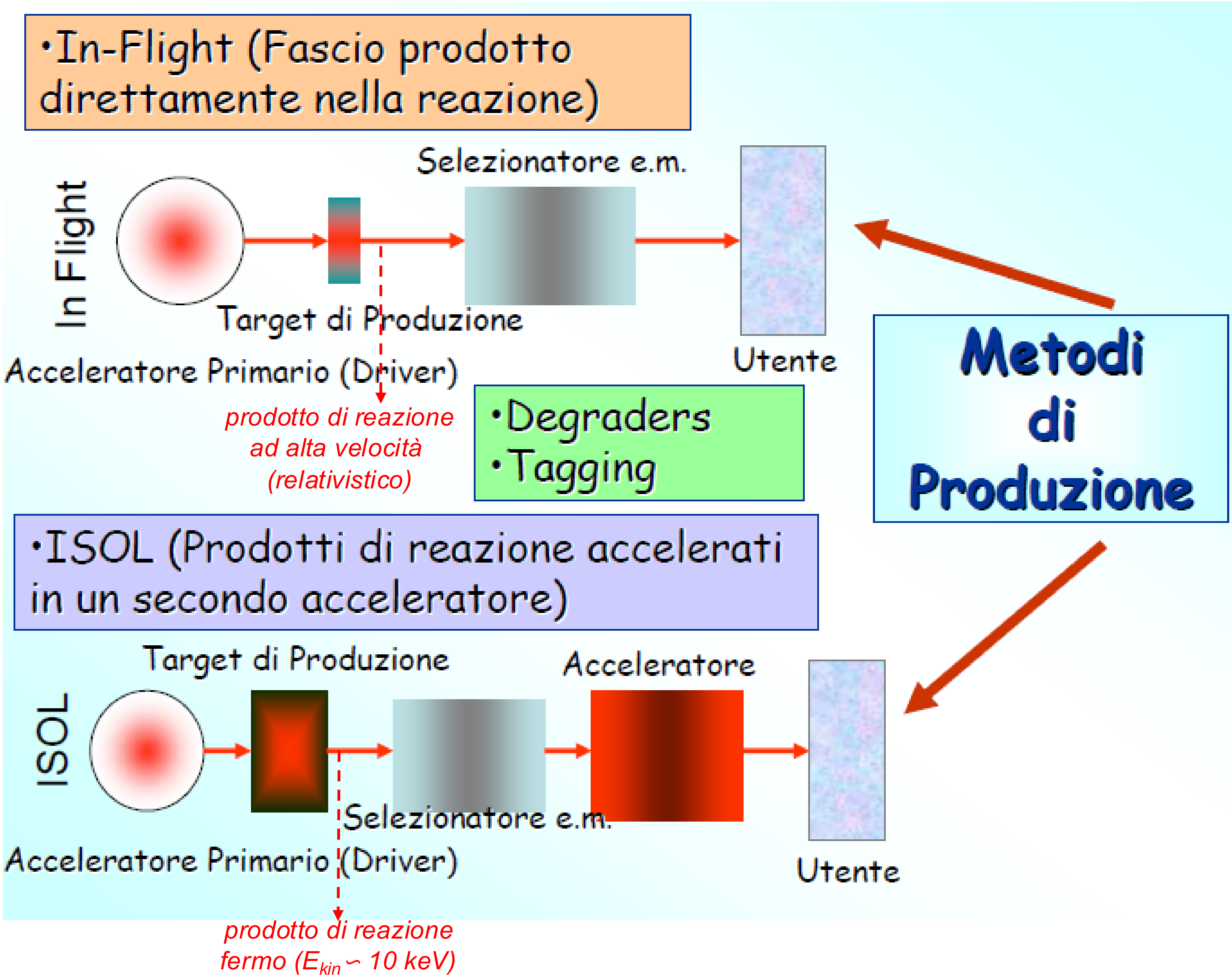
Metodi di produzione

ISOL

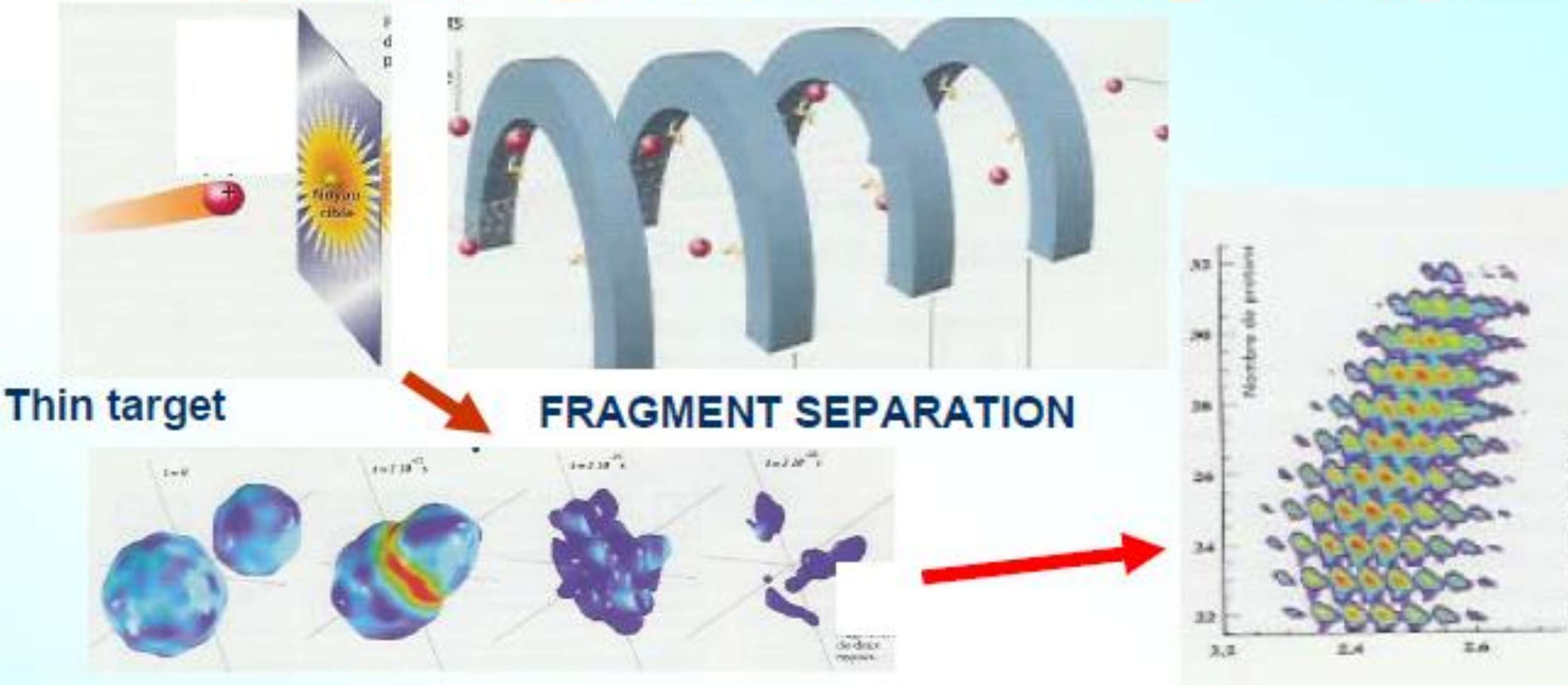
Isotope separation on line
fascio primario p, n, d, …ioni pesanti di massa intermedia (energie da 10 di MeV fino a GeV)

In flight

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


•In-Flight (Fascio prodotto direttamente nella reazione)
In Flight
Selezionatore e.m.
Target di Produzione
Utente
Acceleratore Primario (Driver)
prodotto di reazione ad alta velocità (relativistico)
•Degraders
•Tagging
Metodi di Produzione
•ISOL (Prodotti di reazione accelerati in un secondo acceleratore)
ISOL
Target di Produzione
Acceleratore
Selezionatore e.m.
Acceleratore Primario (Driver)
Utente
prodotto di reazione fermo (E_{kin} ∽ 10 keV)

FRAGMENTATION METHOD



High energy beams

Large spot size and beam cocktails

Exotic Nuclei with short lifetimes < 1ms

Existing facilities:

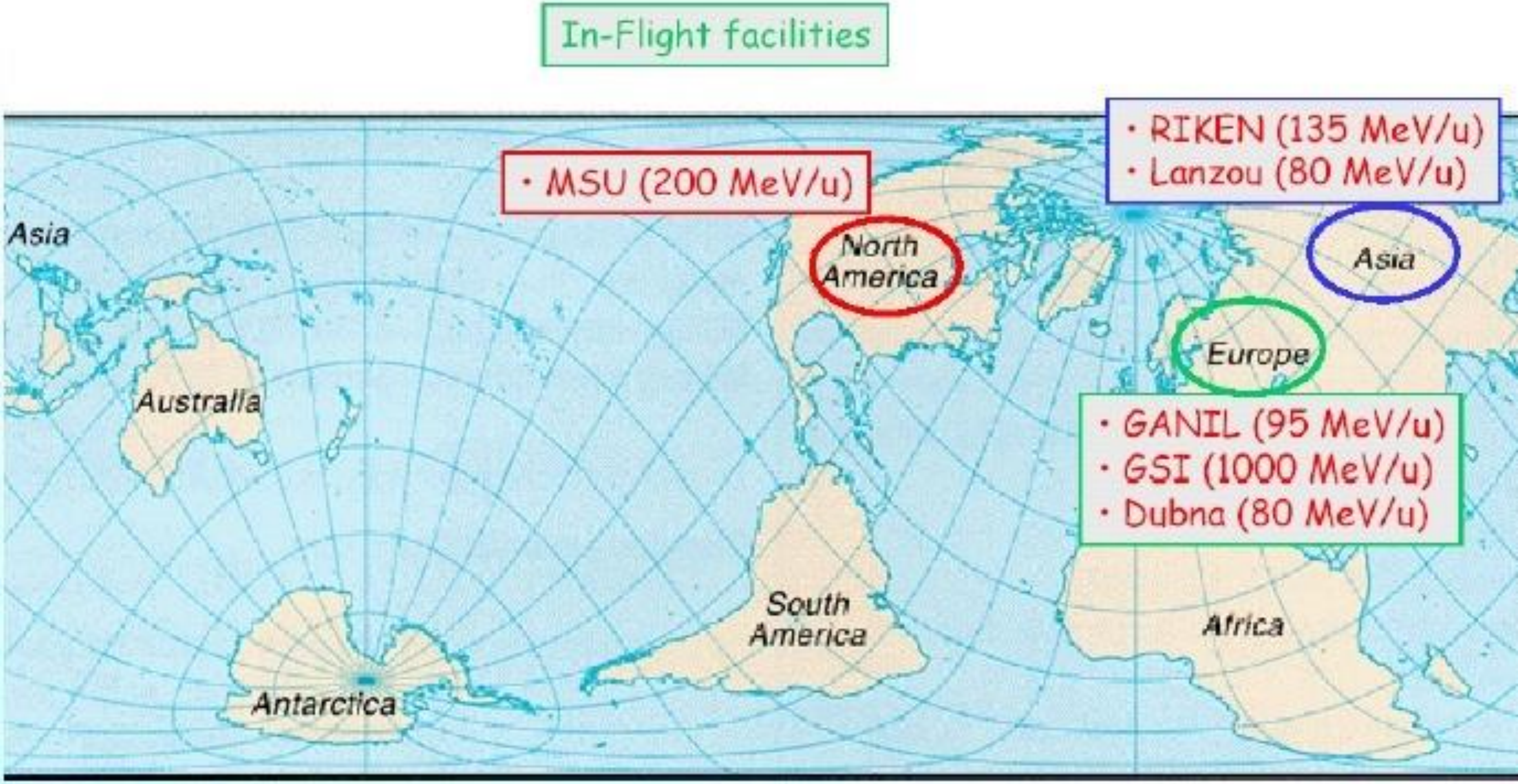
GSI

GANIL

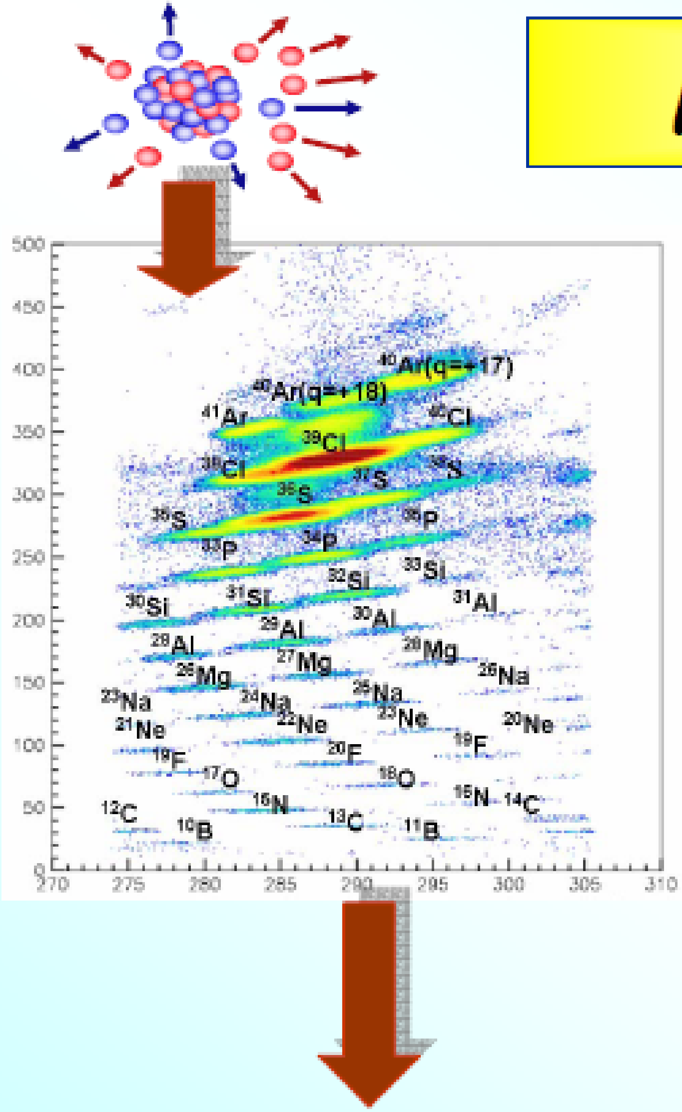
MSU

RIKEN

→ *High energy (relativistic) secondary beams starting from high energy relativistic primary beams*


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)
Asia
North America
Asia
Europe
Australia
South America
Africa
Antarctica

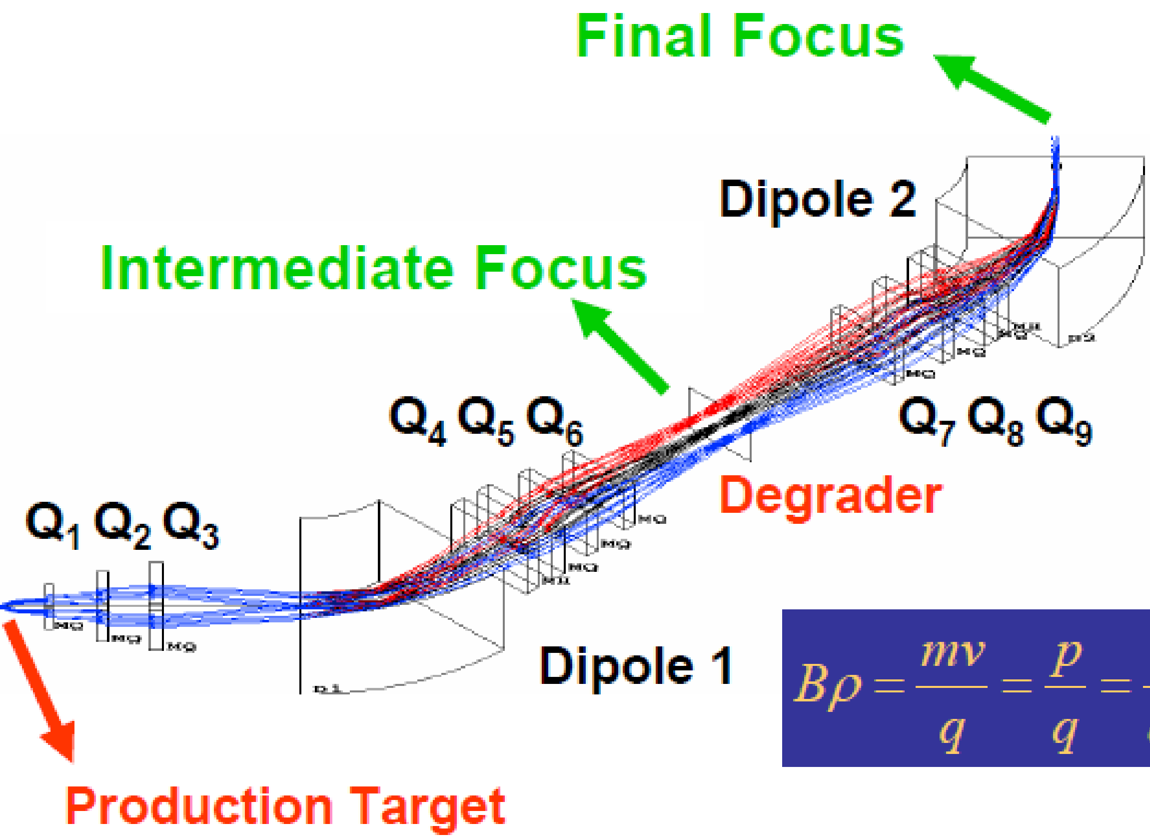
Metodo In-Flight



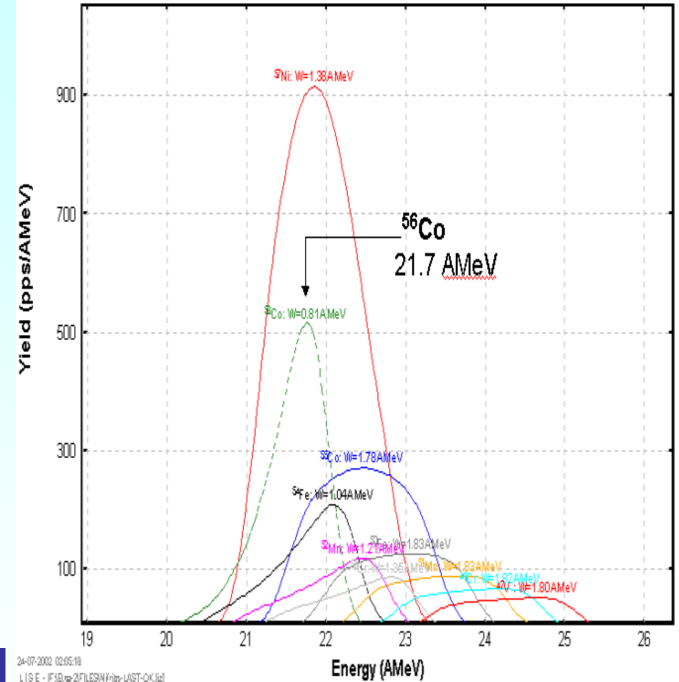
- Relativi problemi di radioattività
- RIBs con vite medie piccole (<msec)

- 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:

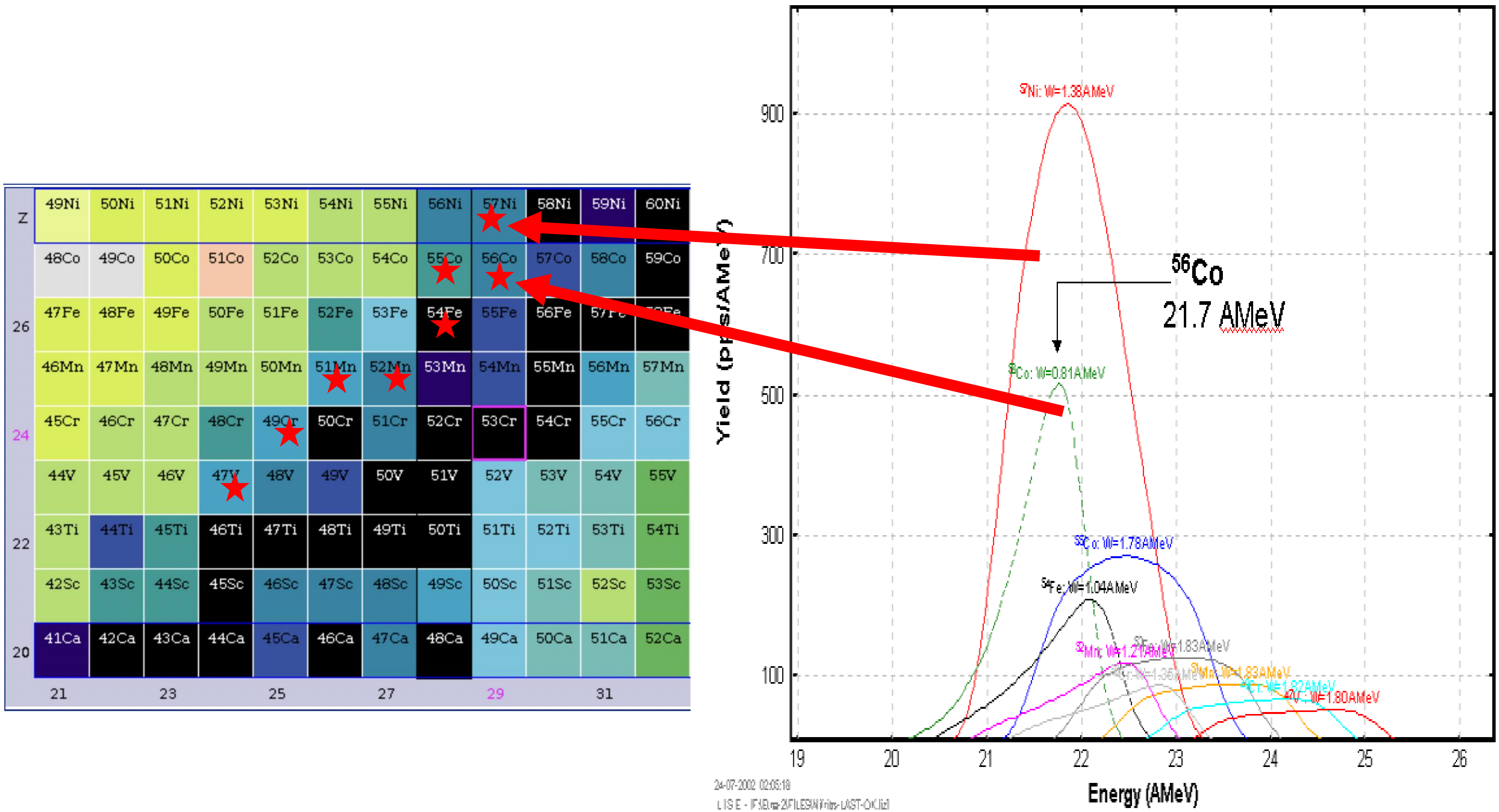
$$\frac{dE}{E} \cong eK\frac{A^3}{Z^2}$$

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

☹ ENERGY STRAGGLING
☹ ANGULAR STRAGGLING
☹ NUCLEAR REACTIONS

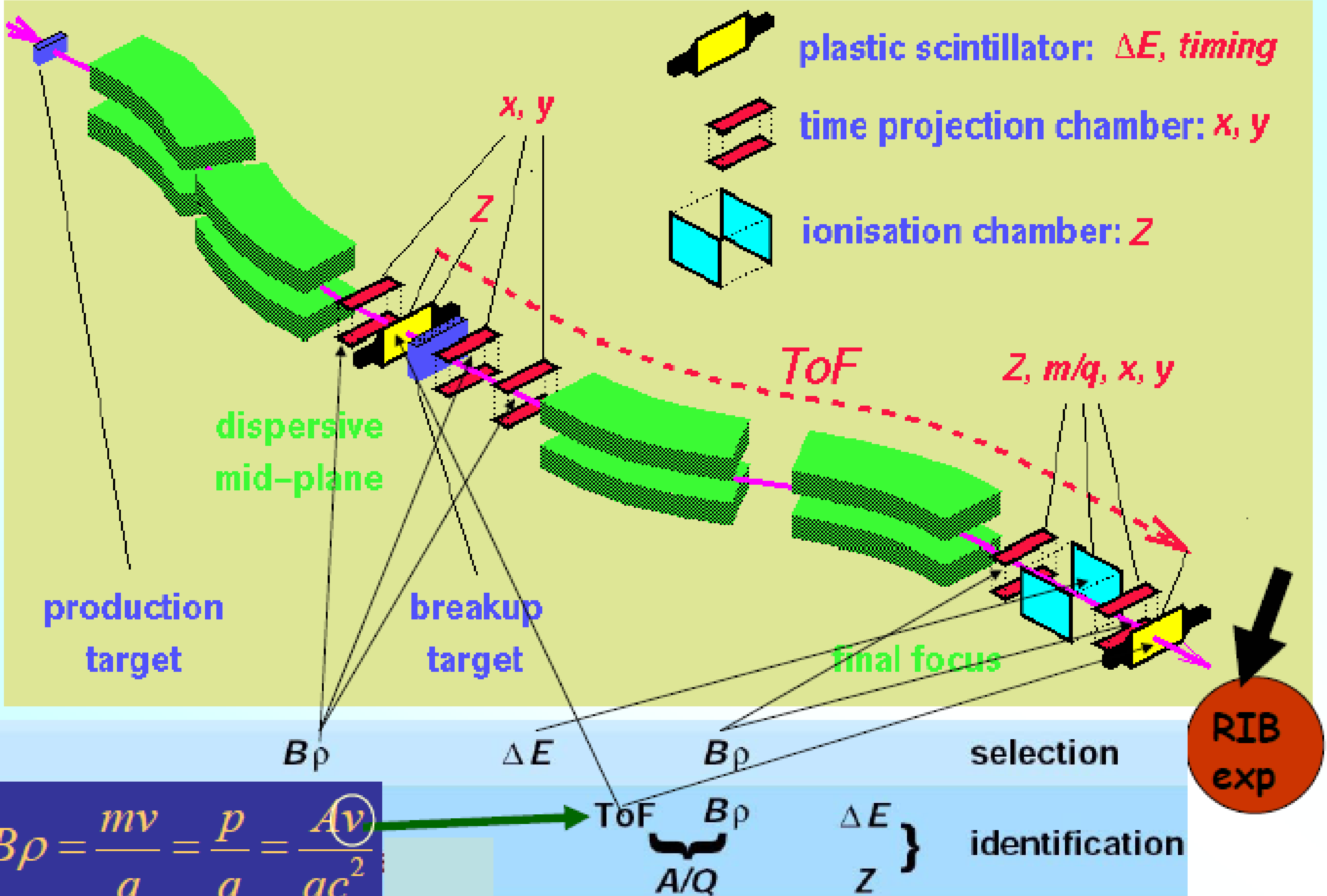
→ INTENSITY LOSS

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



Reduction of “contaminants” can be achieved with the use of a degrader

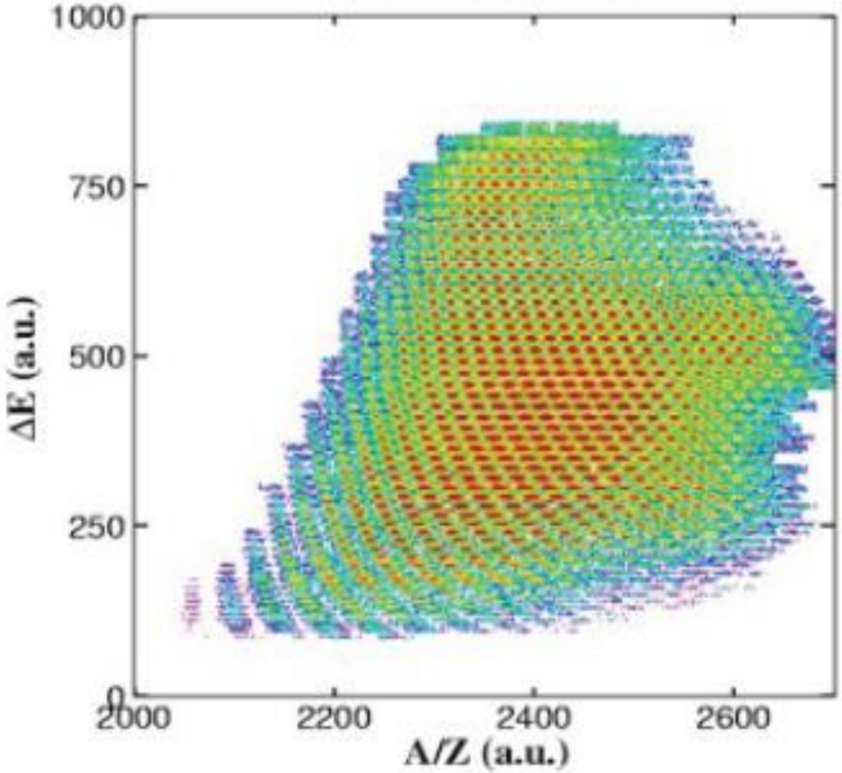
FSR@GSI :



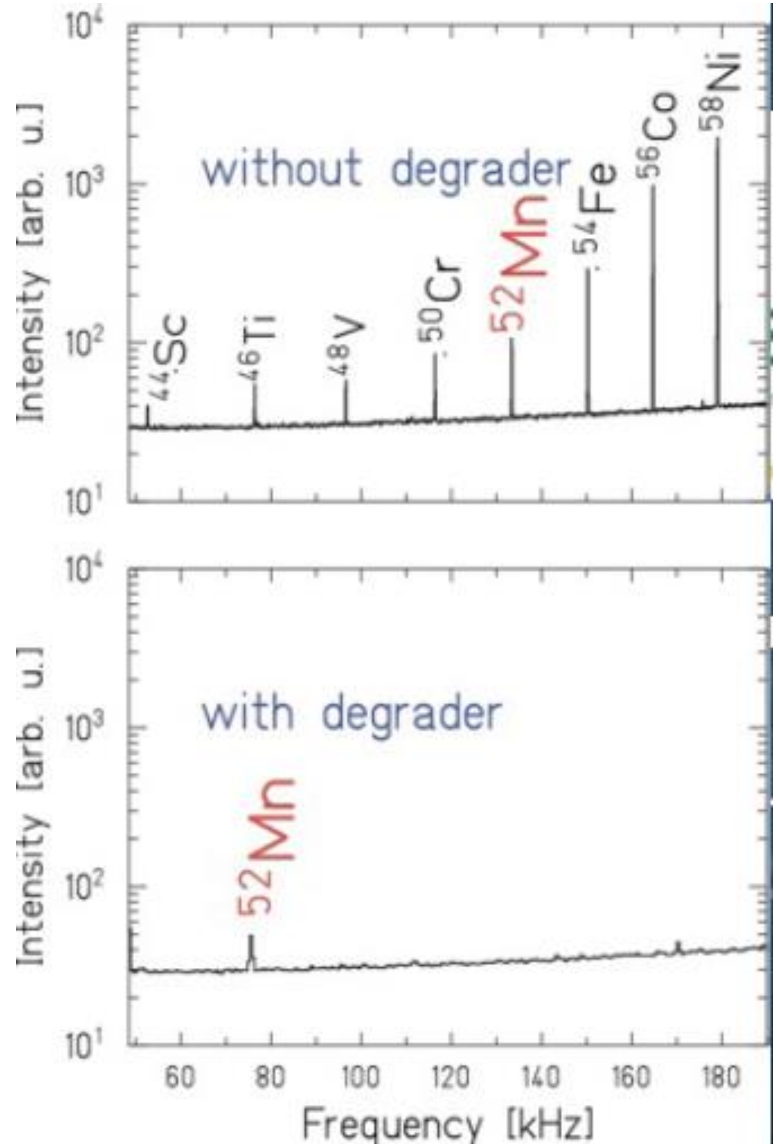
$$B\rho = \frac{mv}{q} = \frac{p}{q} = \frac{Av}{qc^2}$$

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:** *(ISOL-beams: precision physics)*

Spettroscopia gamma

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

Forte complementarietà con fasci da frammentazione
(In-Flight radioactive beams: discovery of new systems, ...)

ISOL TECHNIQUE

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

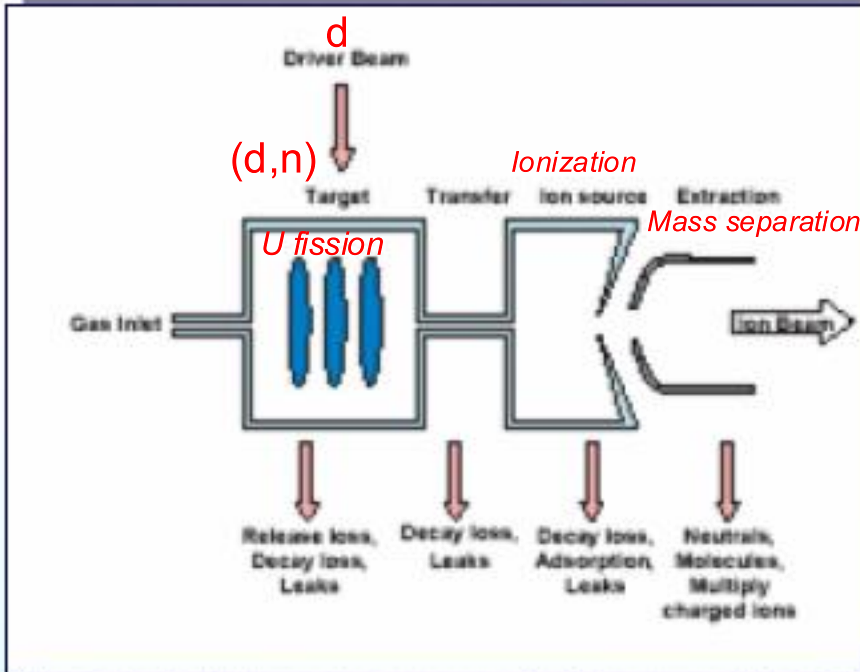
Separation
of the fragments

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

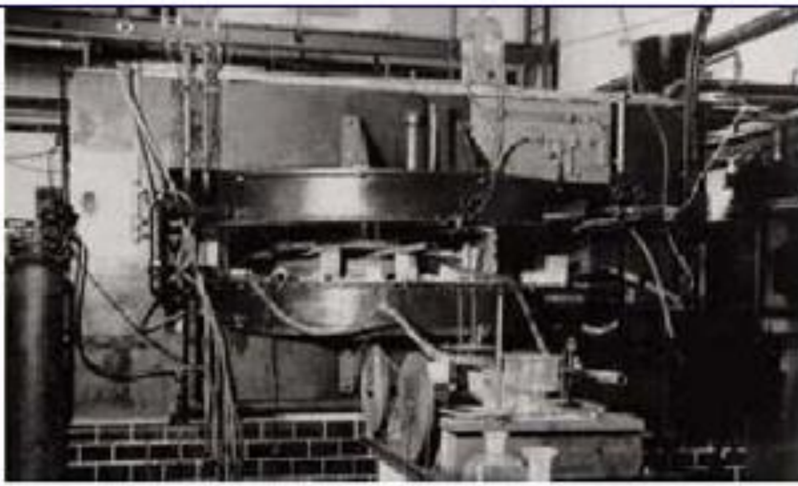


Figure 1: The Niels Bohr Institute cyclotron.

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

This is how ISOLDE started!

https://home.web.cern.ch/news/series/meet-isolde/meet-isolde-where-did-it-all-begin

Short-Lived Krypton Isotopes and Their Daughter Substances

O. Kofoed-Hansen and K. O. Nielsen
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received February 9, 1951)

THE isotopes Kr^{89}, Kr^{90}, Kr^{91}, and their daughter substances have been investigated. Krypton formed in fission of uranium was pumped through a 10-m long tube directly from the cyclotron into the ion source of the isotope separator. The cyclotron and the isotope separator were operated simultaneously, and the counting could begin immediately after the interruption of the separation. The rubidium and strontium daughter substances were separated chemically; strontium was precipitated as carbonate. Half-lives were measured and an absorption analysis of the radiations was carried out. The results are given in Table I.

Table I. Observed radiations.

Isotope	Half-life	Radiation	E_{β}^{max}	Spectrum
Kr^{89}	3.18 min (2.6)	β^-, γ	4.0 Mev	Complex
Kr^{90}	33 sec (33)	β^-, γ	3.2 Mev	Complex
Rb^{90}	2.74 min	β^-, γ	5.7 Mev	Complex
Kr^{91}	10 sec (9.8)	β^-, γ probable	~3.6 Mev	Complex
Rb^{91}	100 sec	β^-, γ	4.6 Mev	Complex
Rb^{91}	14 min	β^-, γ	3.0 Mev	Complex

Previous data (see N.B.S. Circular 499: Nuclear Data) are given in parentheses.

It was found that at least 35 percent of the decays of Kr^{89} lead to an excited state of Rb^{89} which lies ~2 Mev above the ground state. This result is of importance for the interpretation of the β-recoil experiments with this krypton isotope.[1]

Furthermore it was found that Rb^{91} has an isomeric state. Both these states of Rb^{91} (half-lives 100 sec and 14 min, respectively) decay to the well-known Sr^{91} 9.7 hr which again decays to the 60-day and the 50-min isomers of Y^{91}. All these radioactivities were found in the samples of mass number 91.

A more detailed account of the experiments will be published elsewhere.[2]

We wish to thank Professor N. Bohr for his interest taken in our work and Dr. J. Koch for help and advice during this investigation.

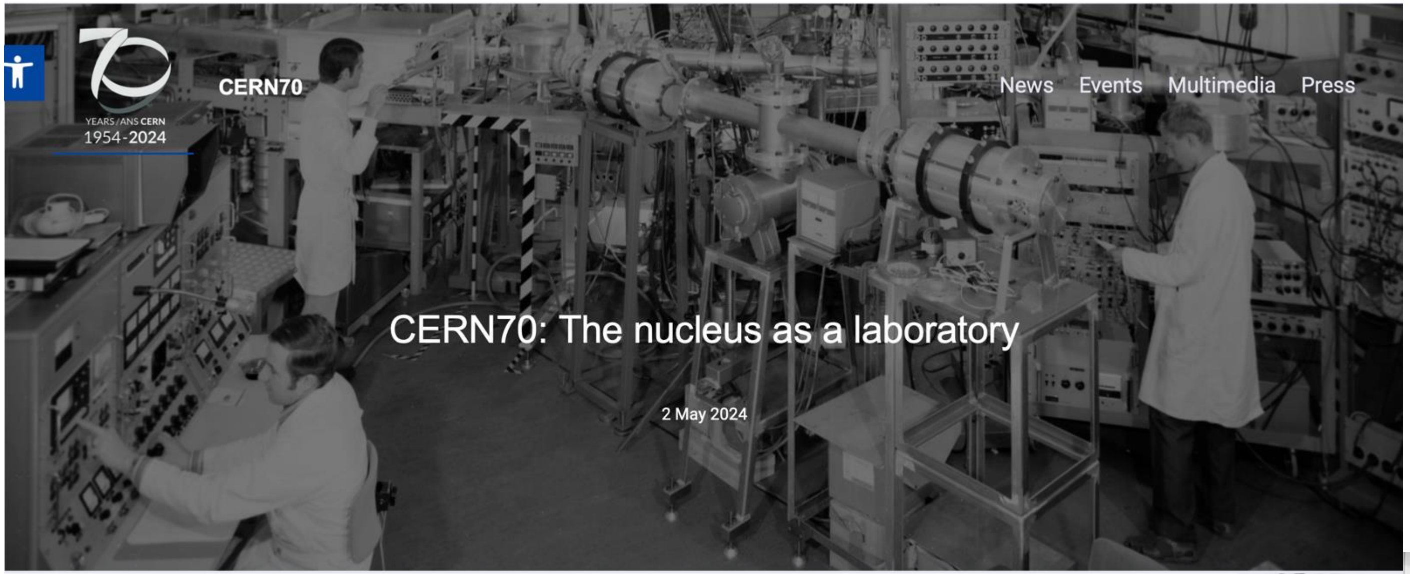
[1] O. Kofoed-Hansen and P. Kristensen, Kgl. Danske Videnskab. Selskab Mat.-fys. Medd. (to be published); see also Phys. Rev., preceding letter.
[2] O. Kofoed-Hansen and K. O. Nielsen Kgl. Danske Videnskab. Selskab Mat.-fys. Medd. (to be published).

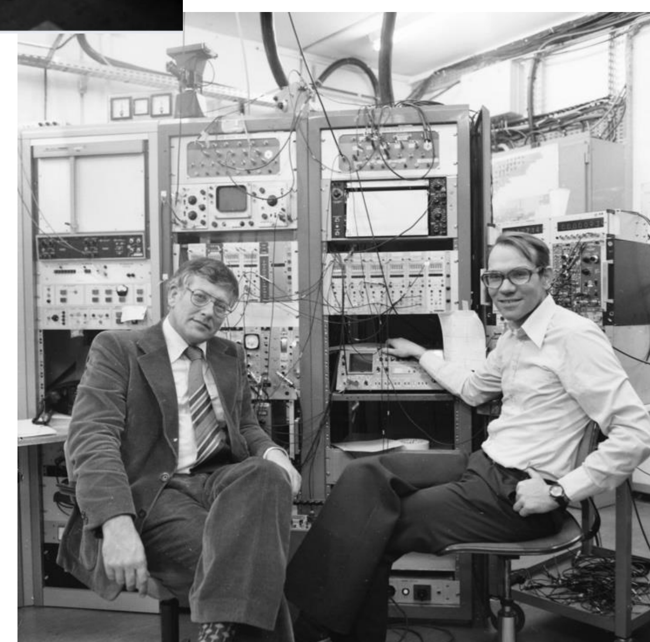
Letter to the Editor
Phys. Rev. ***82****, 96 (1951)*
Published 1 April 1951

This is how ISOLDE started – first beam in 1967!

https://home.web.cern.ch/news/series/meet-isolde/meet-isolde-where-did-it-all-begin

https://cern70.cern/cern70-the-nucleus-as-a-laboratory/

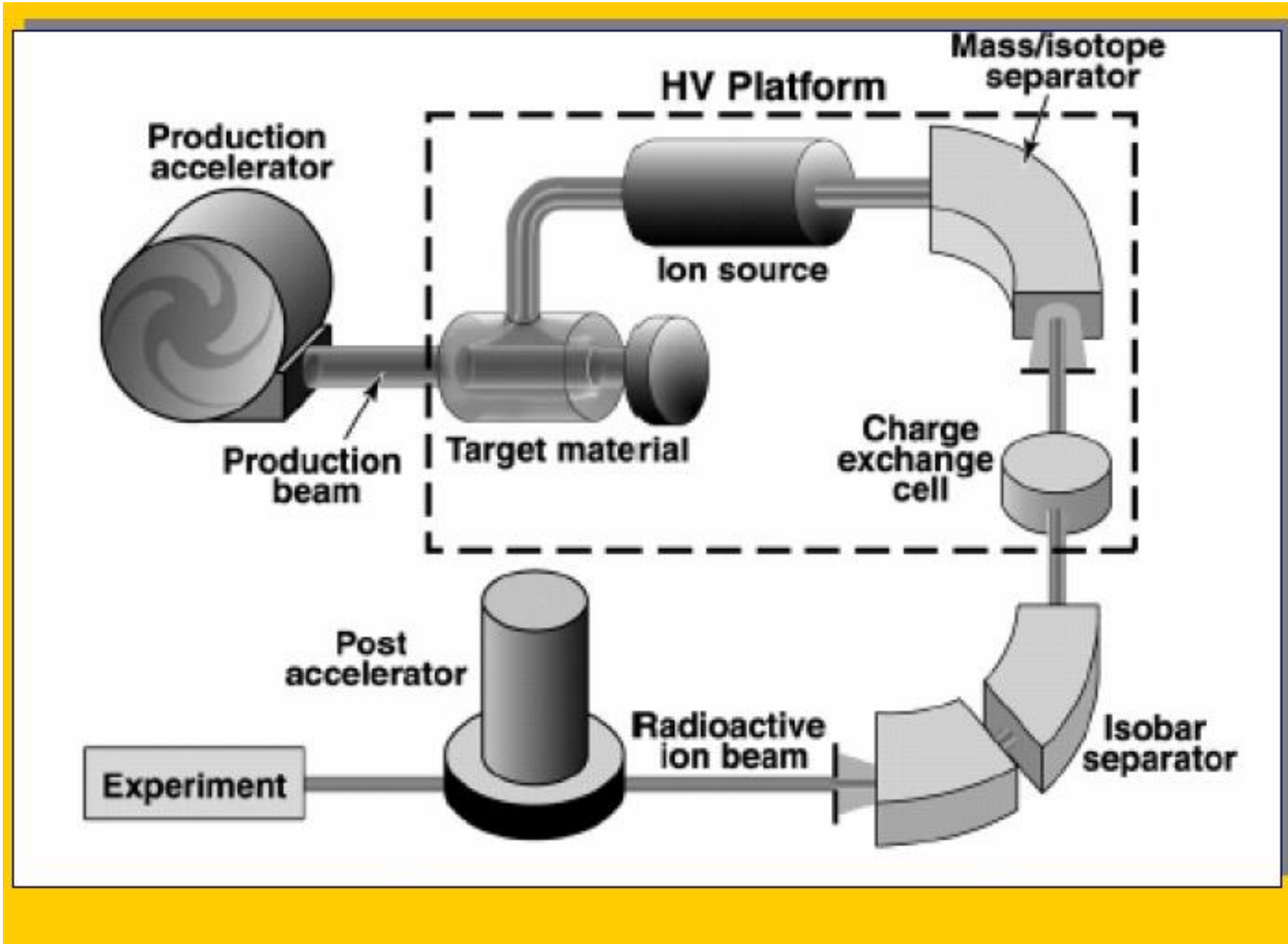




When **ISOLDE** was started, it was mainly a **Scandinavian undertaking**. The nucleus of the CERN Nuclear Chemistry group that hosted ISOLDE was composed of Danes, Swedes and Norwegians and we often joked that the DE in ISOLDE stood for Danish Engineering.

Helge Ravn

Similar ISOL production scheme in today's facilities



Intensità particelle prodotte

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

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.

Efficiency loss can be up to a factor of 100

$\Phi \times N$ = Luminosity

Metodo ISOL

Isotopes
Separation
On
Line

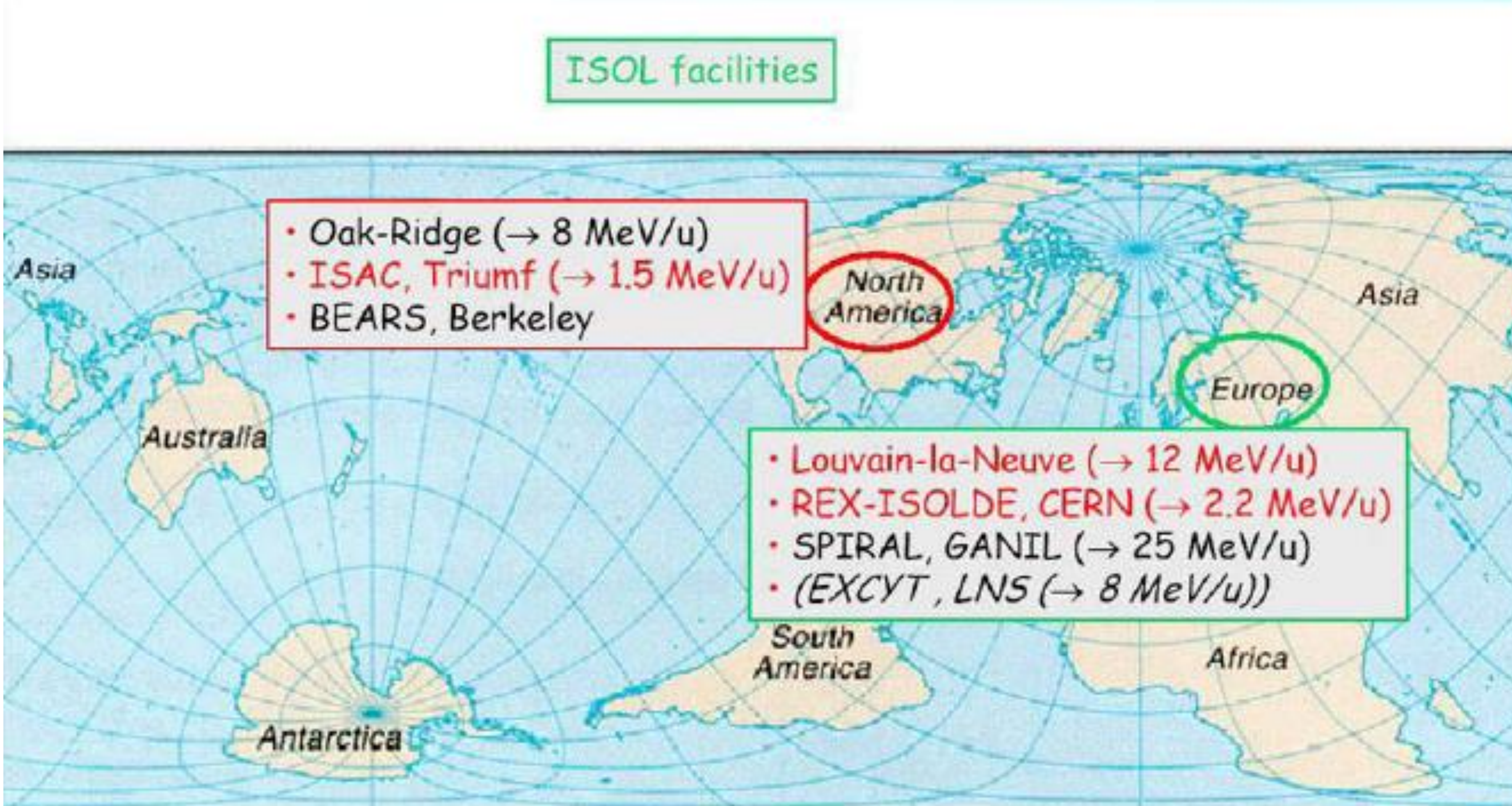
- Driver ad alta intensità (Dissipazione Calore)
- Targhette di produzione (Raffreddamento e Radioattività)
- Efficienza Selezione(20%)
- Efficienza di estrazione (30%)
- Efficienza di Trasmissione alla Sorgente(30%)

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

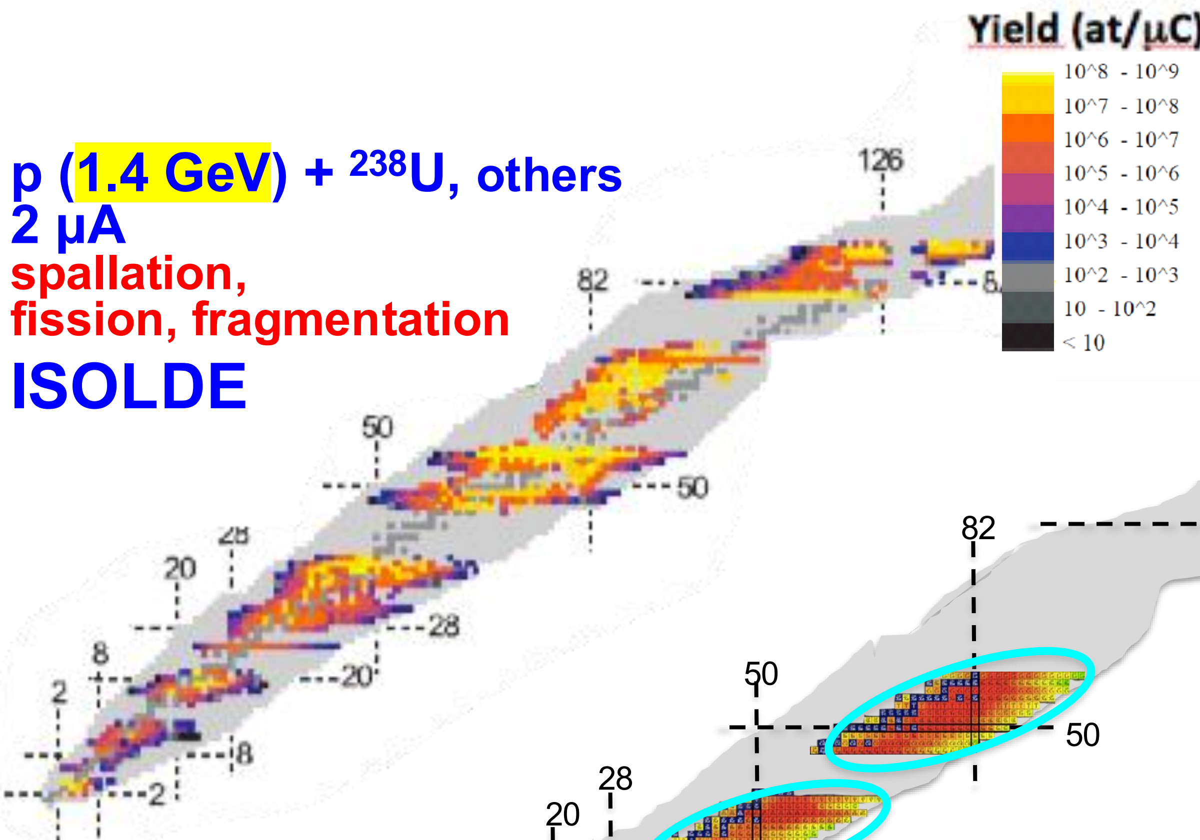


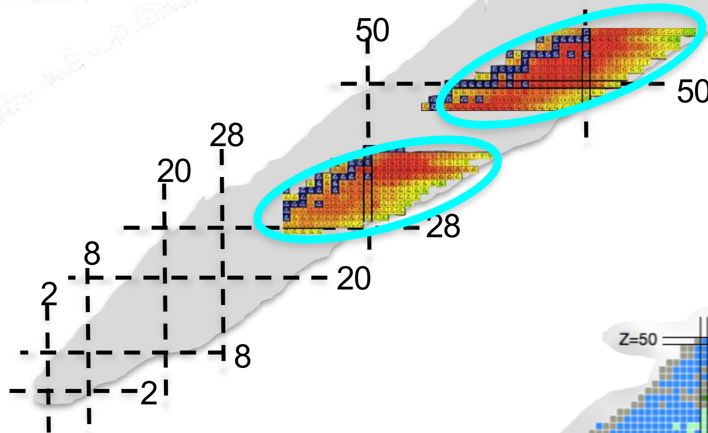
Potenze del fascio del driver primario di pochi kW

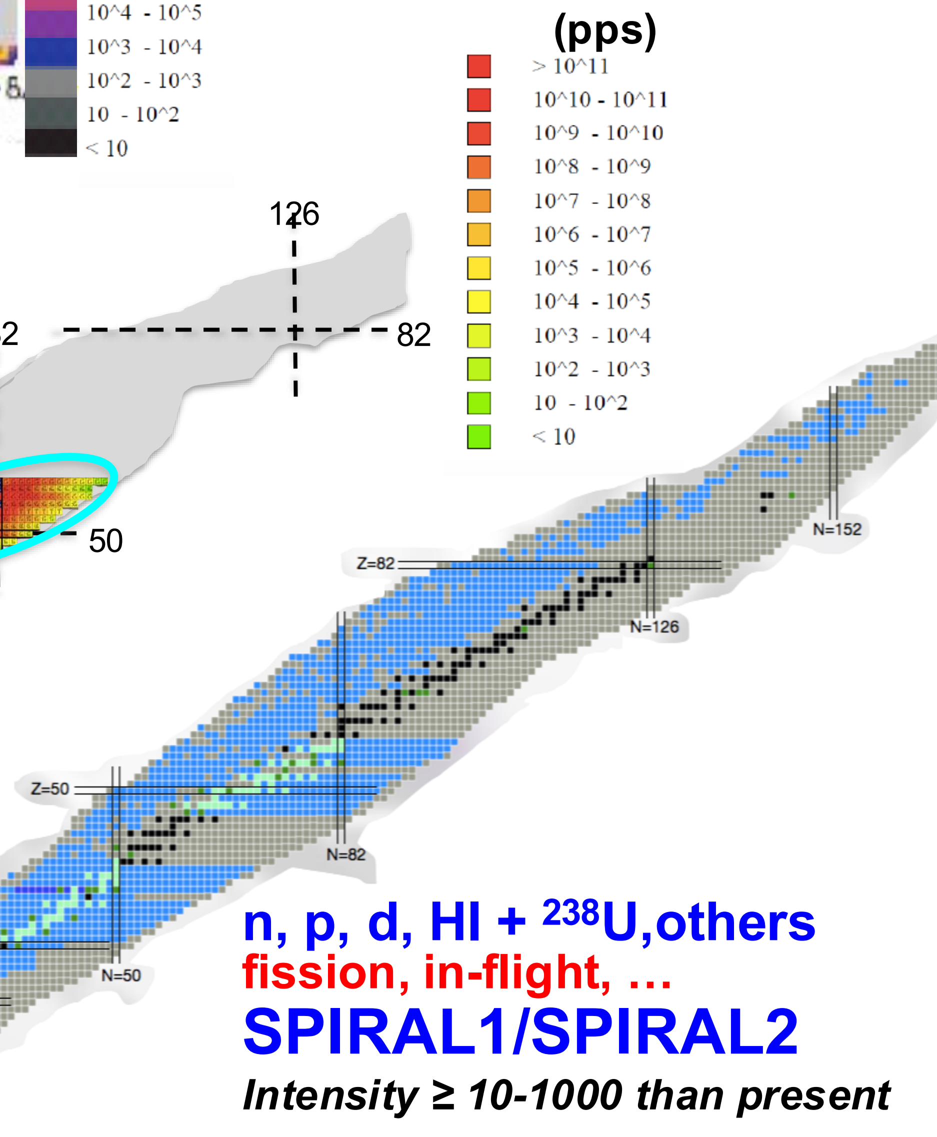
ISOL Facilities in Europe-Production Schemes

p (1.4 GeV) + ^{238}U, others
2 μA
spallation,
fission, fragmentation

ISOLDE







p (40 MeV) + ^{238}U
200 μA
fission

SPES

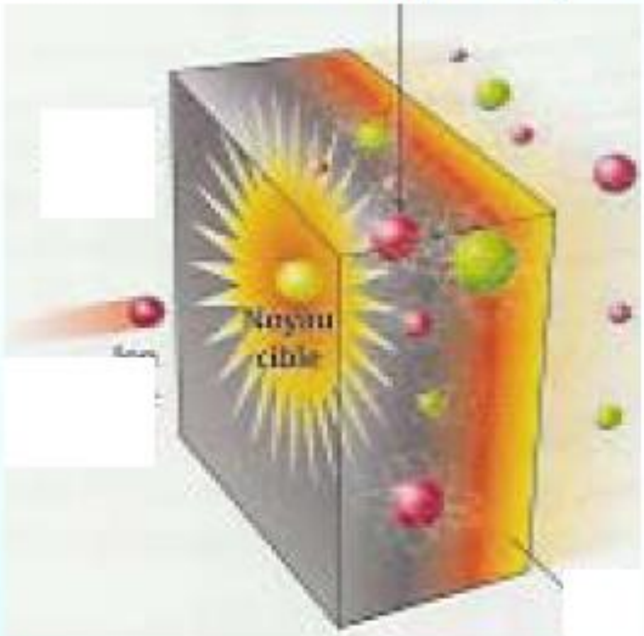
n, p, d, HI + ^{238}U,others
fission, in-flight, …

SPIRAL1/SPIRAL2

Intensity ≥ 10-1000 than present

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

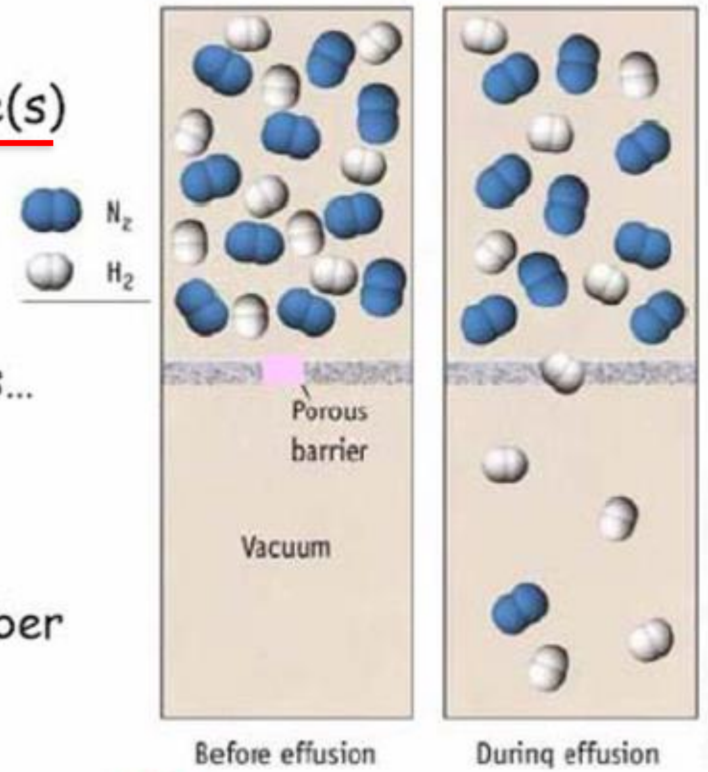
Diffusione : e' il processo attraverso il quale la materia e' trasportata da una parte all'altra come risultato del moto molecolare di tipo random
Serve un gradiente termico

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

+ meccanismo di <u>effusione per uscire</u> dalla superficie

2. Effusion

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



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

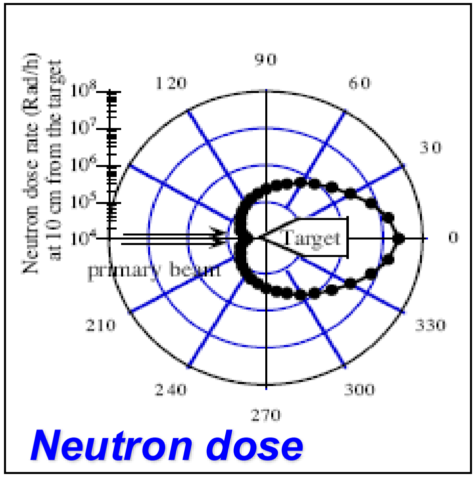
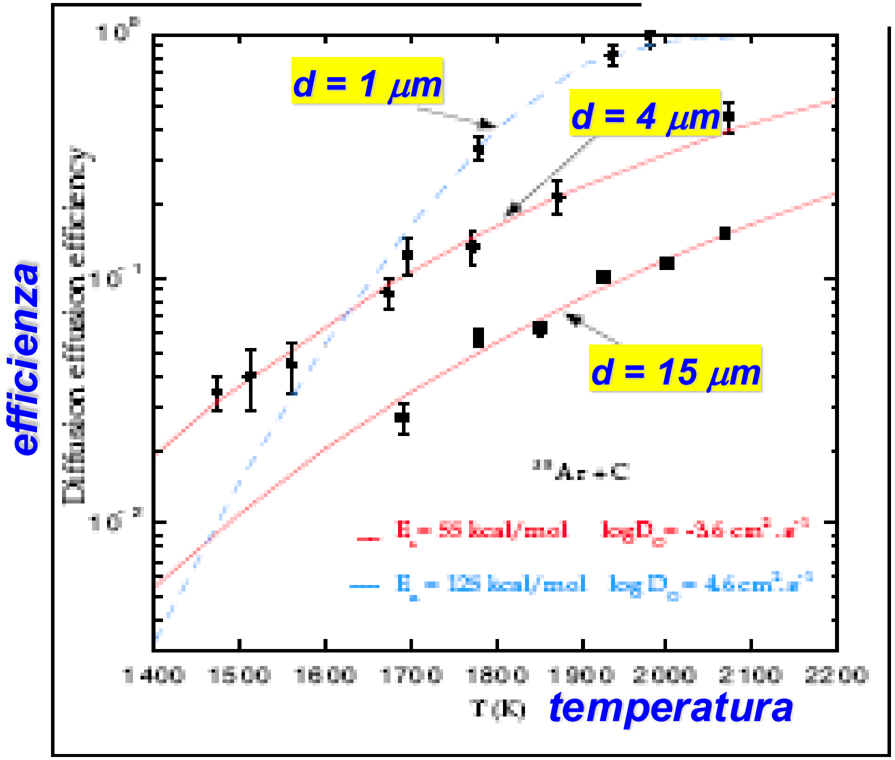


Figure 6 : Predicted angular distribution of the neutron dose for a 6 kW ³⁶S primary beam.

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



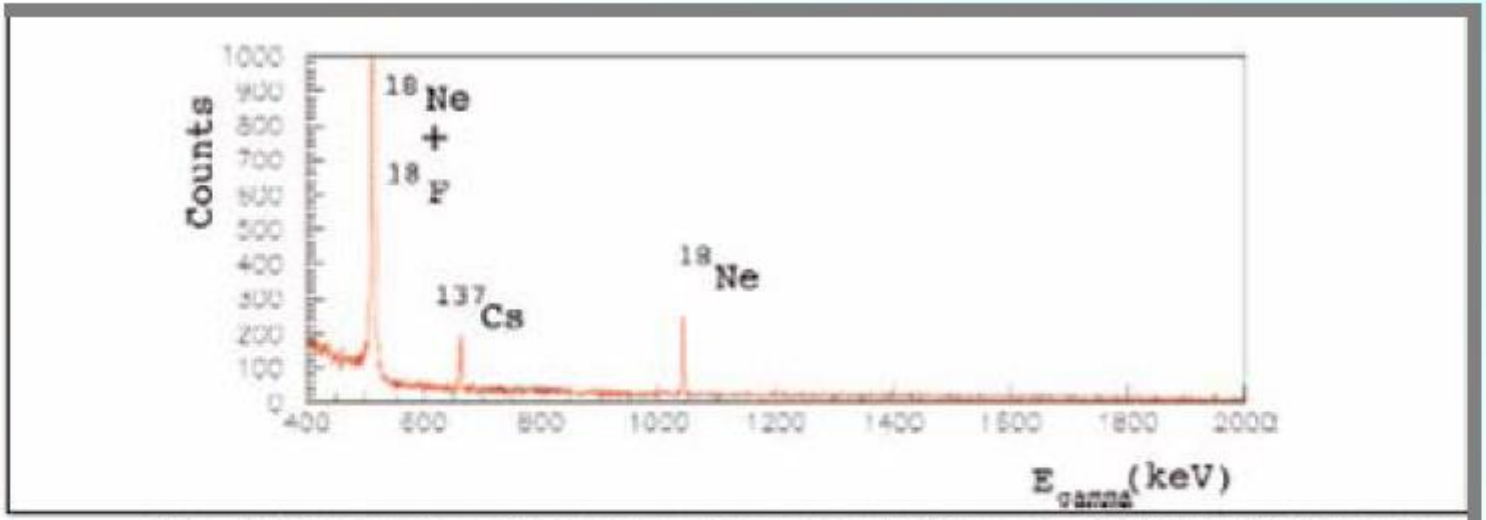


Figure 3 : Energy spectrum of the germanium detector during the first experiment at SPIRAL. The ^{18}Ne is clearly identified with the 1041 keV gamma ray. The 671 keV is emitted by the ^{137}Cs of the calibration source used.

Check beam purity with gamma spectroscopy!

Ottima qualità dei Fasci ISOL

N.B. all’uscita del target di produzione i fasci ISOL sono «fermi»

(hanno energie di ∽ 10 keV).

Possono essere usati per studi di beta-decay o post-accelerazione

Resonant Laser Ionization sources (RILIS)

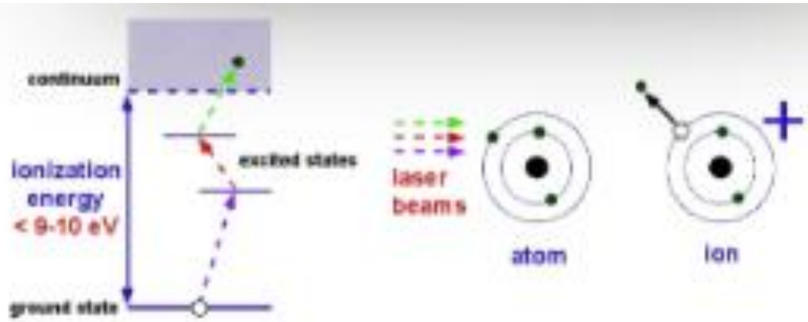
for on-line mass separators for radioactive ion beams

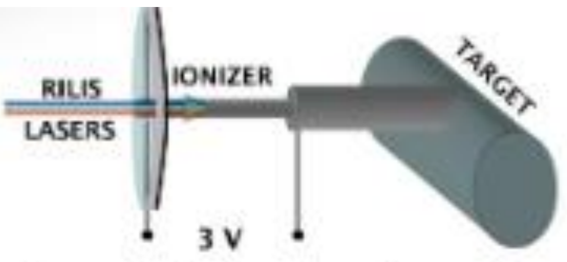
The RILIS is a chemically selective ion source which relies on resonant excitation of atomic transitions using tunable laser radiation

*A **laser is tuned to a wavelength** which excites only one isotope of the material and ionizes those atoms preferentially.*

*The **resonant absorption** of light for an isotope is dependent upon its mass and certain hyperfine interactions between electrons and the nucleus, allowing finely tuned lasers to interact with only one isotope.*

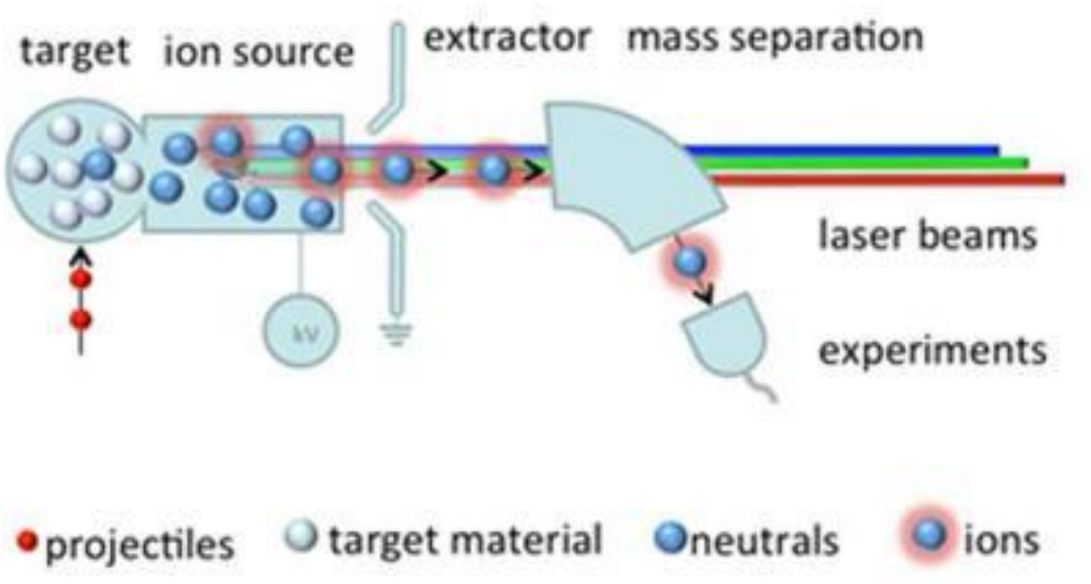
*After **the atom is ionized** it can be removed from the sample by applying an electric field.*

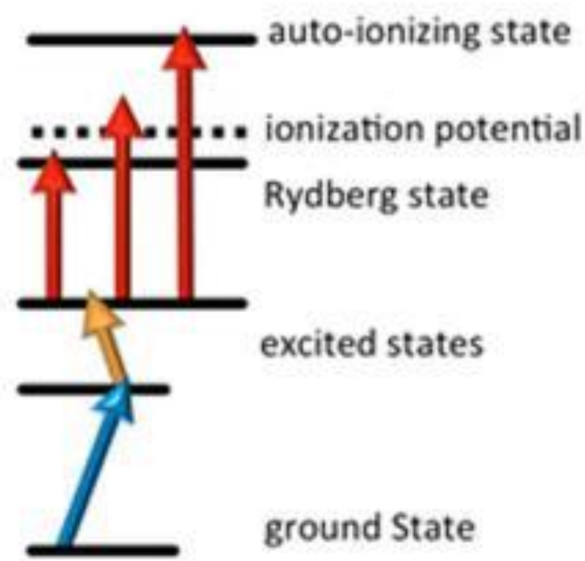




Laser ionization in a hot cavity

RILIS @ ISOLDE-CERN

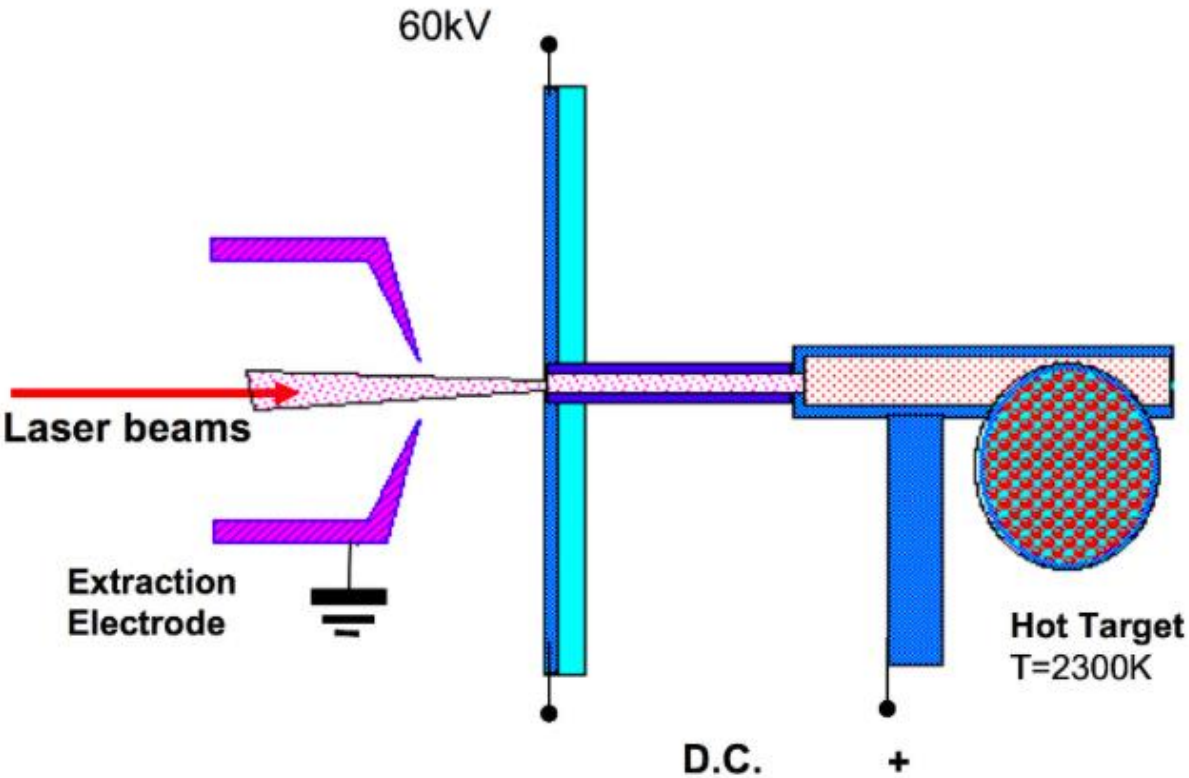




a preliminary study
of the *atomic properties* is needed
to establish the ionization scheme:
a **research field by itself**!

20-40 % efficiency of ionization

RILIS @ ISOLDE-CERN



Efficiency:

$$\varepsilon = \frac{P_{Ionisation}}{P_{Ionisation} + P_{Effusion}}$$

$$\varepsilon = \frac{\nu_{rep}\,\varepsilon_{ion}}{\nu_{rep}\,\varepsilon_{ion} + \frac{2dv}{3L^2}}$$

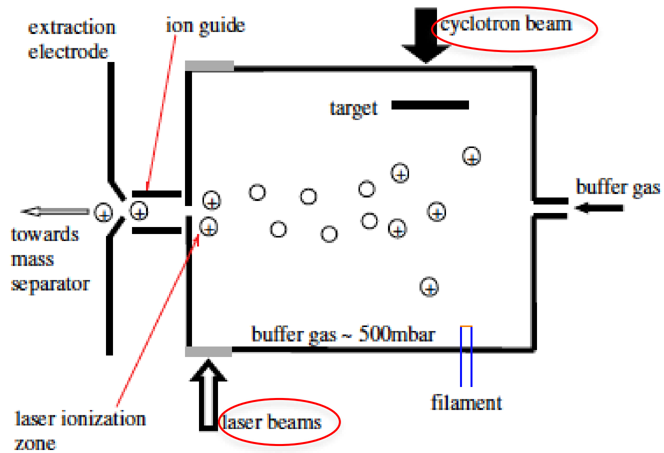
$\varepsilon_{surface}$

> 5% - alkalis

ε_{laser} = 1% - 30%

$$\text{Selectivity} = \frac{\text{Laser Ionization Efficiency}}{\text{Surface Ionization Efficiency}}$$

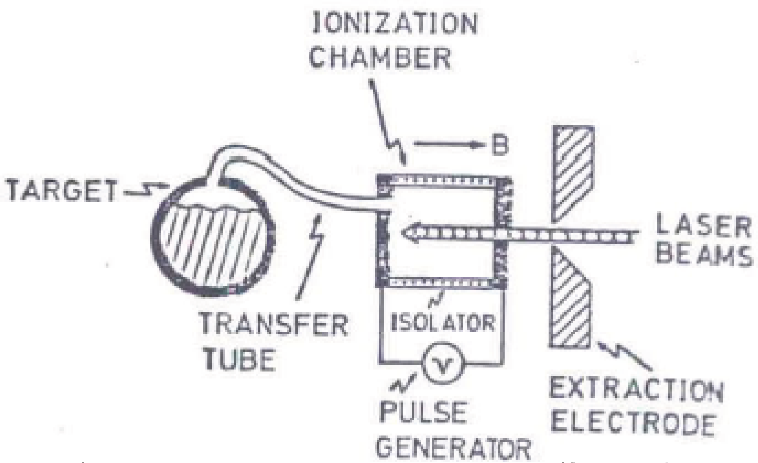
=> depends on the ionization potentials of isobar atoms

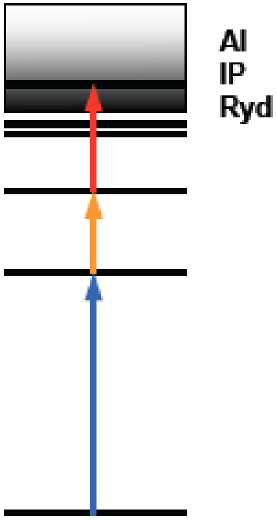


For on-line isotpe separators the main advantages are the pulsed structure of the extracted radioactive beam and the reduction of isobaric impurites.

...

Ionization efficiencies of the order of 20 to 40% are expected for elements with one atomic ground state populated thermally. ..."



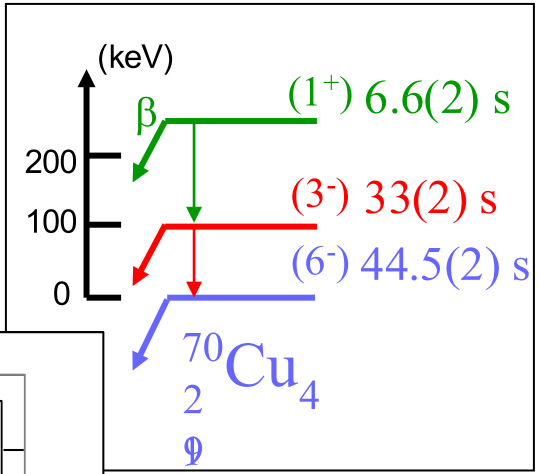


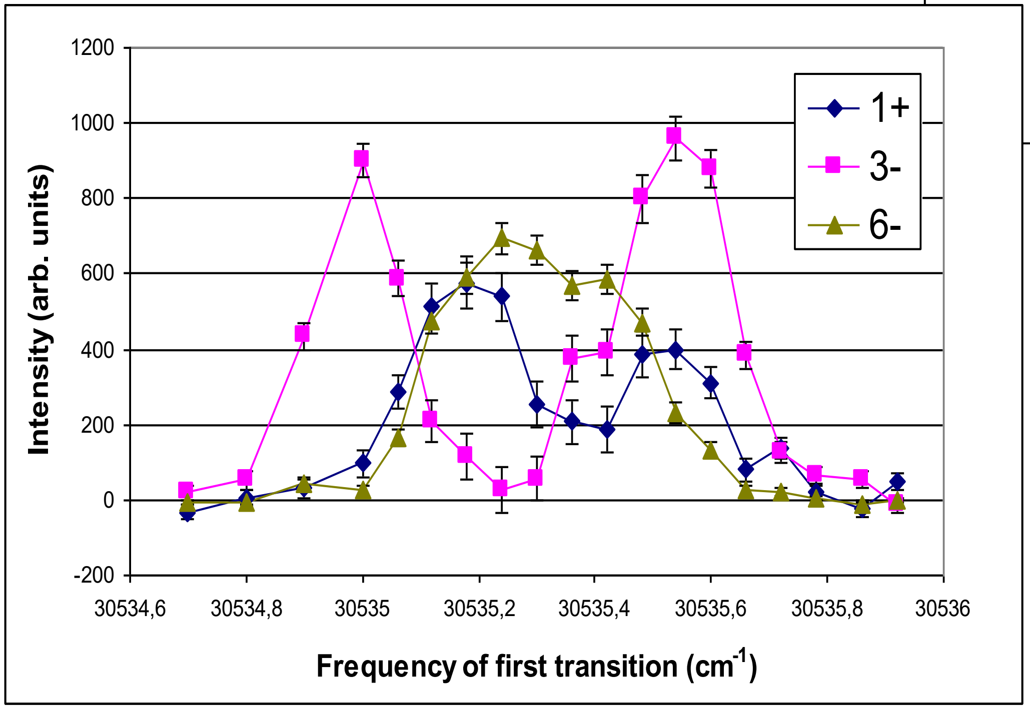
H.-J. Kluge, F. Ames, W. Ruster, K. Wallmeroth, Accelerated Radioactive Beams Workshop, Parksville B.C., Canada Sept 5-7 (1985)

RILIS : efficient, fast, clean

Production of isomeric beams: $^{70}Cu^{m1,m2,g}$

- laser ionization in a hot cavity
- different hyperfine splitting for the different isomers
- enhancement of specific isomers

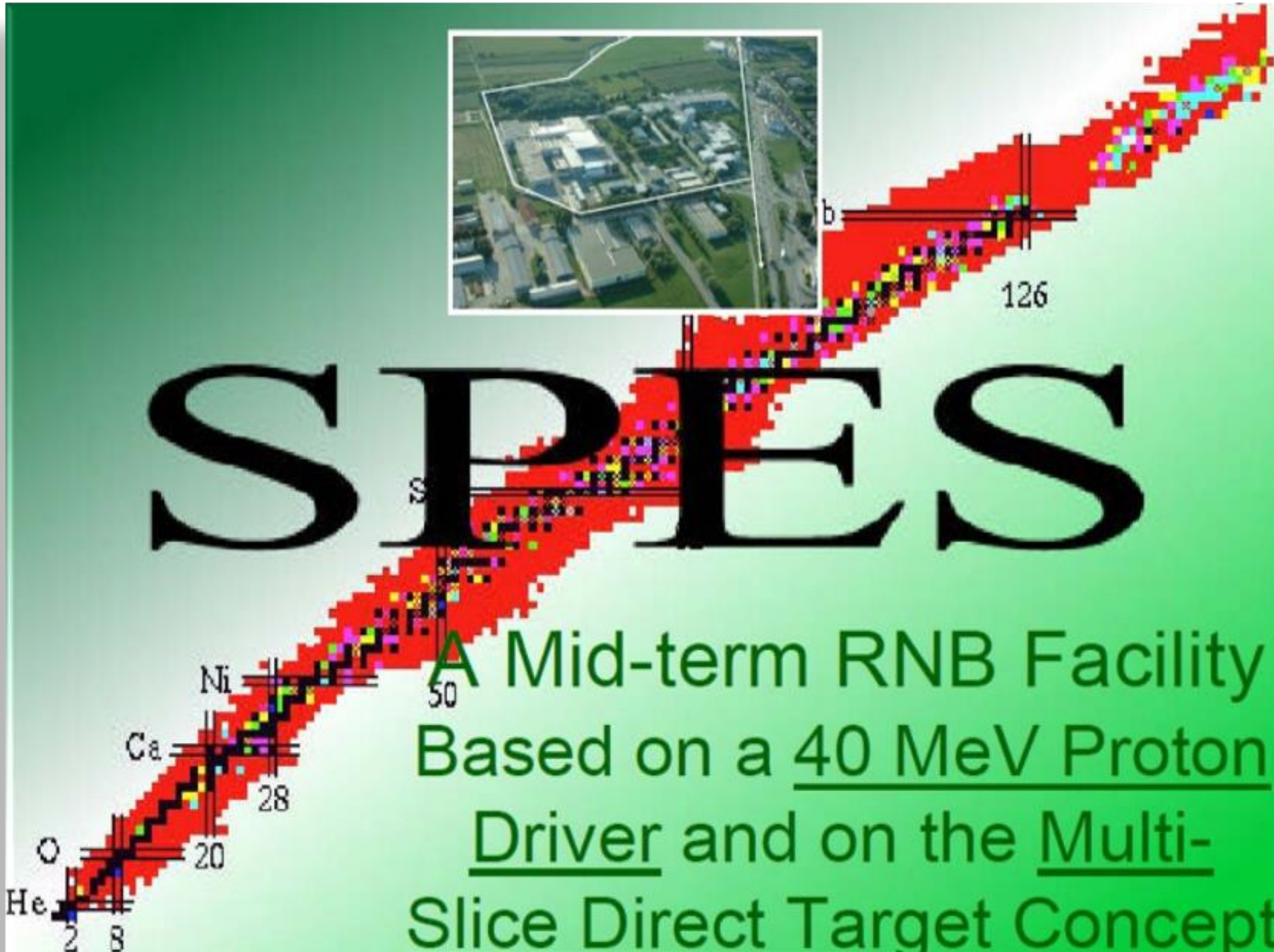




V. Fedoseev, U. Koster,
J. Van Roosbroeck et al., ISOLDE

- increase **selectivity** of laser ion sources
- reduce power, pressure and Doppler broadening

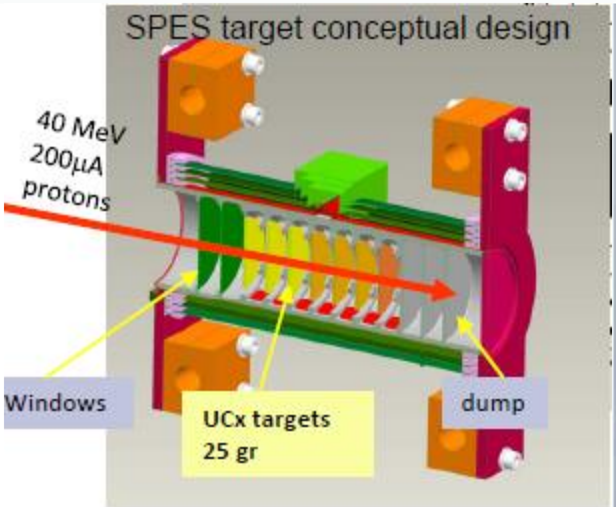
Progetto Italiano per fasci Radioattivi (Laboratori Nazionali di Legnaro)

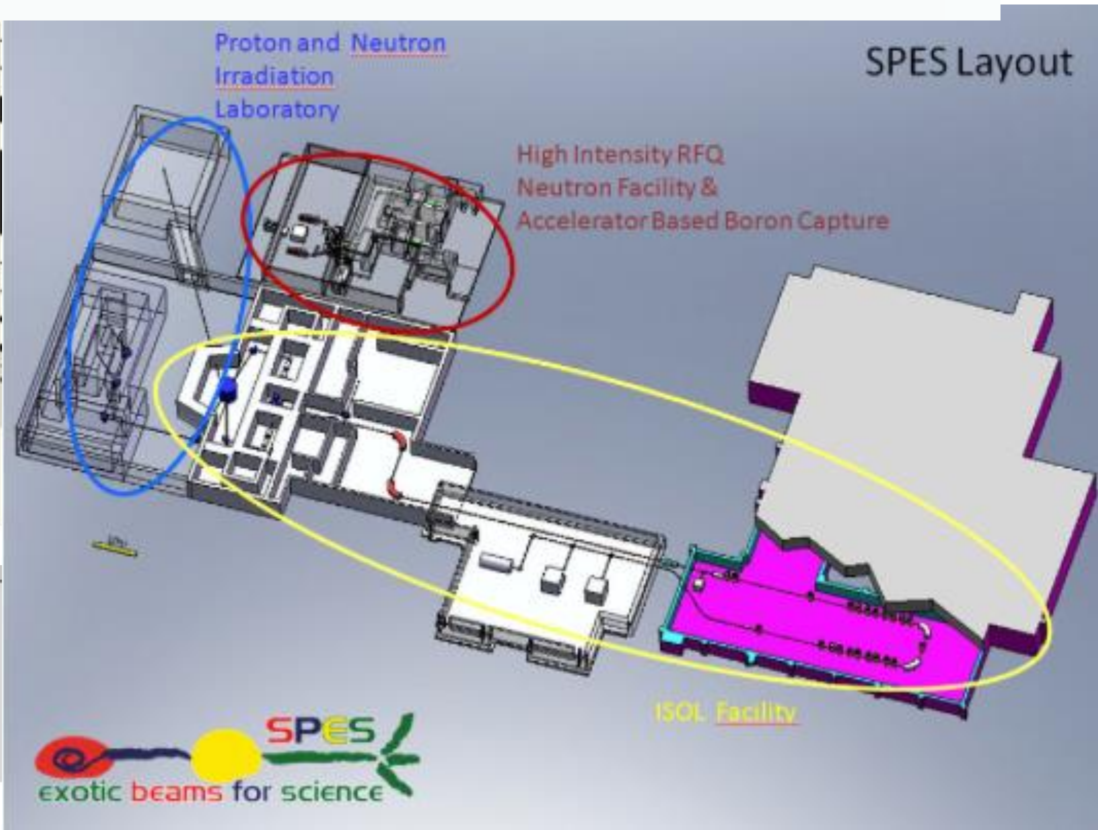


Radioactive Beam Project at Legnaro Laboratory INFN - Italy

SPES
exotic beams for science

- Radioactive Ion Beams are produced by proton induced fission on a UCx direct target at a rate of 10^{13} fission/s.
- Neutron rich re-accelerated beams will be available at energies up to 13 MeV/u in the mass region A=130.
- Re-acceleration will be performed by the superconducting linear accelerator complex (PIAVE-ALPI) of the Laboratori Nazionali di Legnaro.
- The facility for applied physics is based on proton and neutron beams from a two exit port cyclotron (70 MeV, 500 microA) and the high intensity RFQ TRASCO (5 MeV, 30 mA).

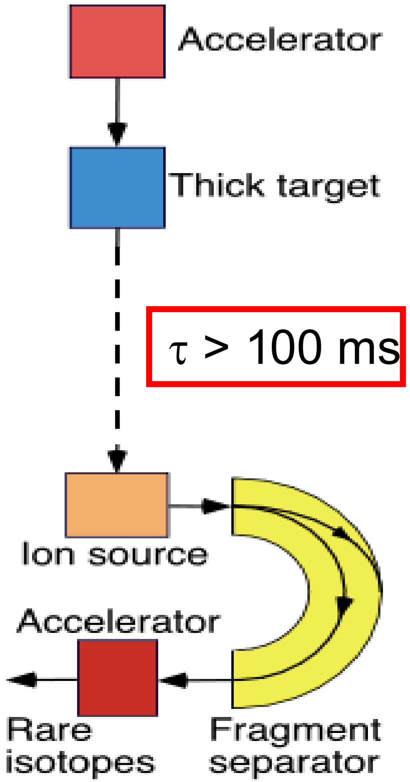




ISOL target
operated at 2000° C
Ionization
and extraction
with 1+ Plasma source

Radioactive Beams

ISOL (Isotope Separation on Line)



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)

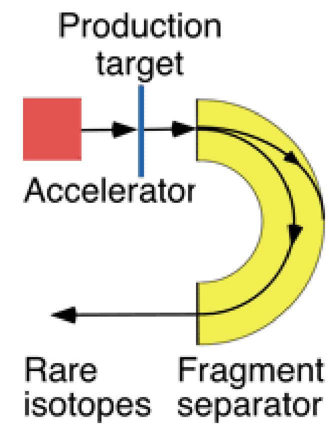
- diffused atoms are collected
- ionized
- separated
- re-accelerated

Advantages: excellent beam quality

Disadvantages: development of diffusion process for each elements

Rex-Isolde: 3.1 MeV/A (Z=2-88), $\approx 10^4$-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

$\tau < 1\ \mu s$

Advantages:
no chemical processes involved,
high-intensity beams

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

...