CANS
– Compact Accelerator-driven Neutron Sources

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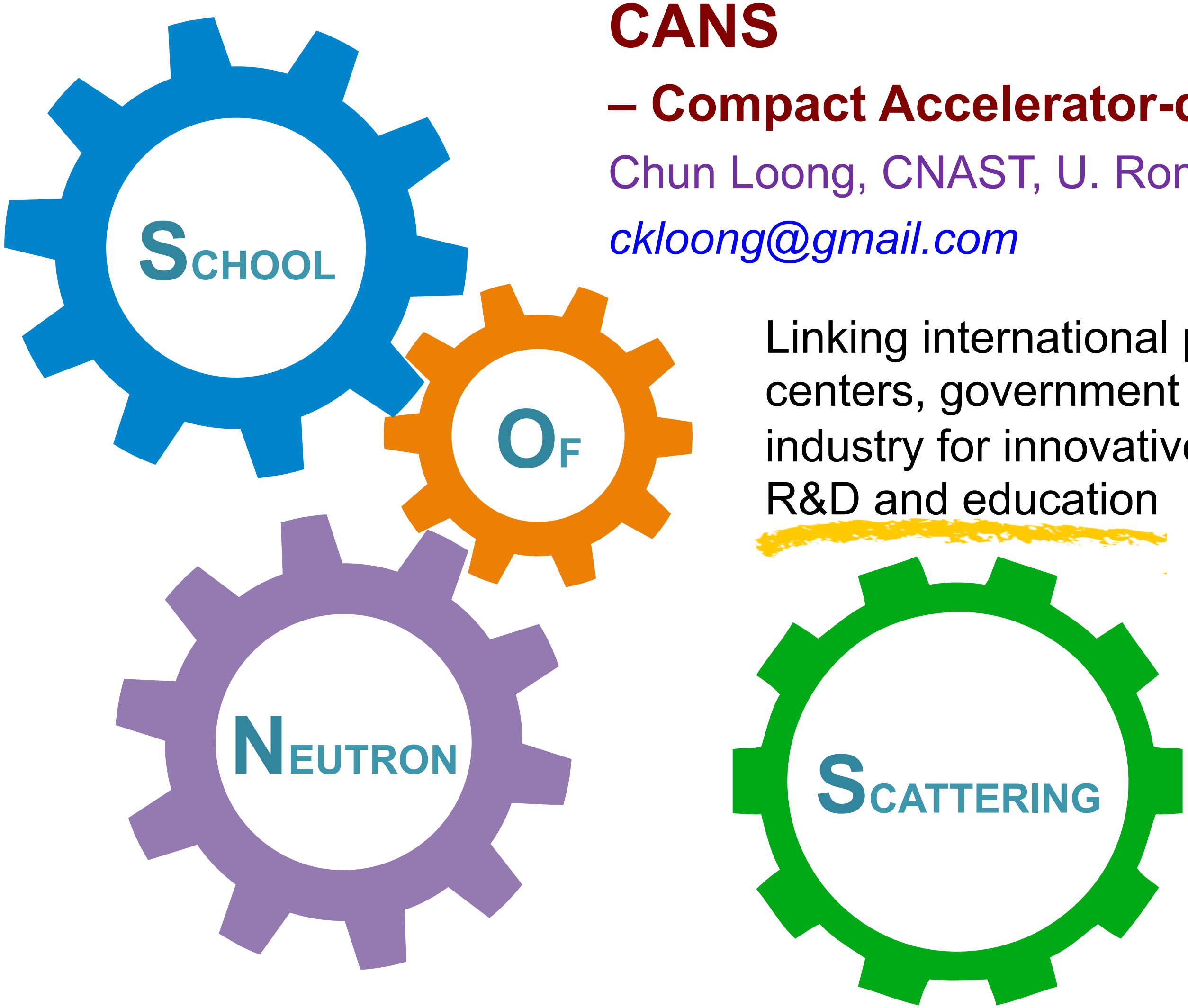


Linking international projects, regional centers, government labs, universities, & industry for innovative neutron applications – R&D and education

30 April-9 May, 2014 ENCSC-Erice

Outline

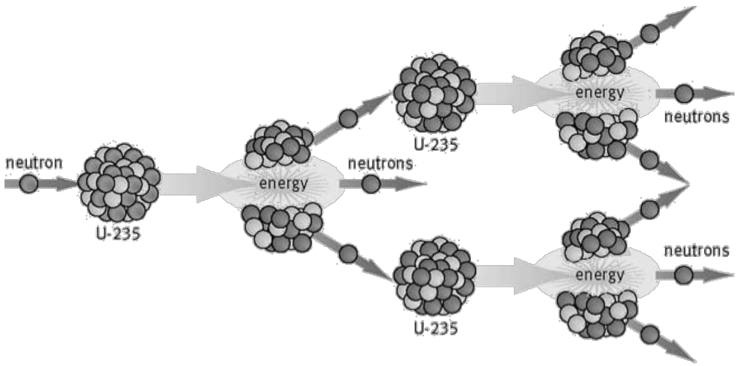
1 Neutron sources
- ✧ Big, medium, and small ones and their roles in R&D
- ✧ The Compact Accelerator-driven Neutron Sources (CANS): higher potential for innovative applications

2 Finding the niches
- ✧ Innovation and inventiveness through combined utilization of unique capabilities of CANS
- ✧ Illustrative examples—ideas for brainstorming

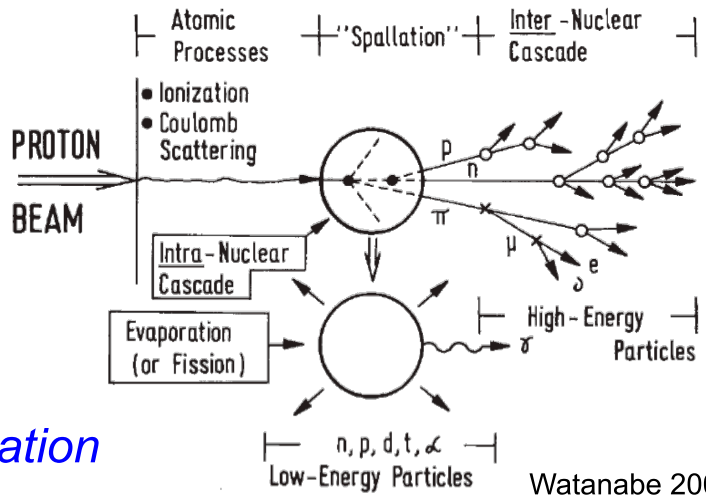
3 The road to applications
- ✧ Taking note of the multidisciplinary nature and diverse utilization

Neutron Production Mechanisms

Reactions	Neutron Production
Fission	$^{235}U + n \longrightarrow A^* + B^* + xn; \quad <x> \sim 2.5$
Spallation	$p + {}^{184}W \longrightarrow A^* + B^* + xn, \quad <x> \sim 20$
Photoproduction	$\gamma + {}^{181}Ta \longrightarrow {}^{180}Ta + n, \gamma + {}^{2}H \longrightarrow {}^{1}H + n$
Charged-particle reaction	$^{9}Be + p \longrightarrow {}^{9}B + n, {}^{2}H + {}^{3}H \longrightarrow {}^{3}He + n$
(n,xn)	$^{9}Be + n \longrightarrow {}^{8}B^* + 2n$
Excited-state decay	$^{13}C^{**} \longrightarrow {}^{12}C^* + n, {}^{130}Sn^{**} \longrightarrow {}^{129}Sn^* + n$



Fission



Spallation

Watanabe 2003

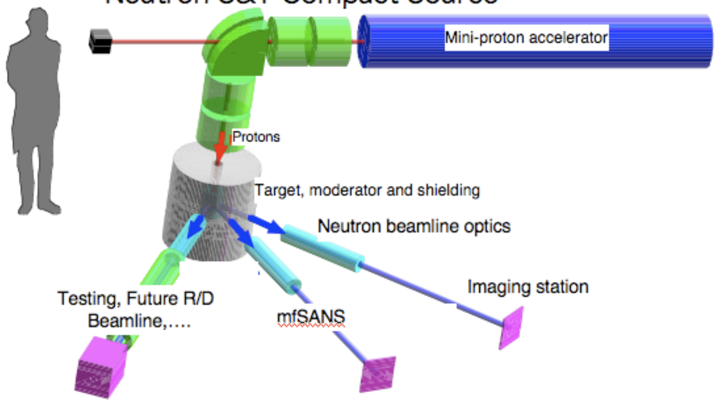
Neutron Sources

Big

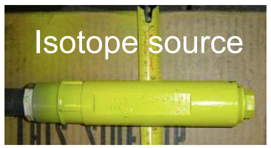
Medium

Compact Accelerator-Driven Sources

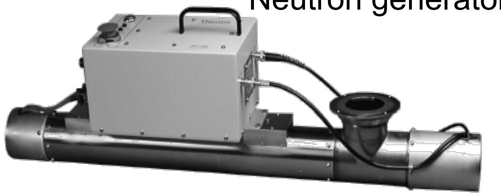
Neutron S&T Compact Source

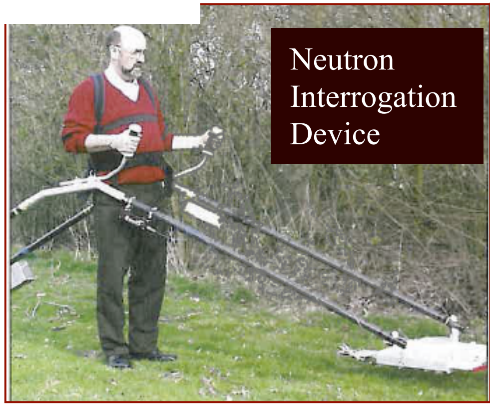


Small

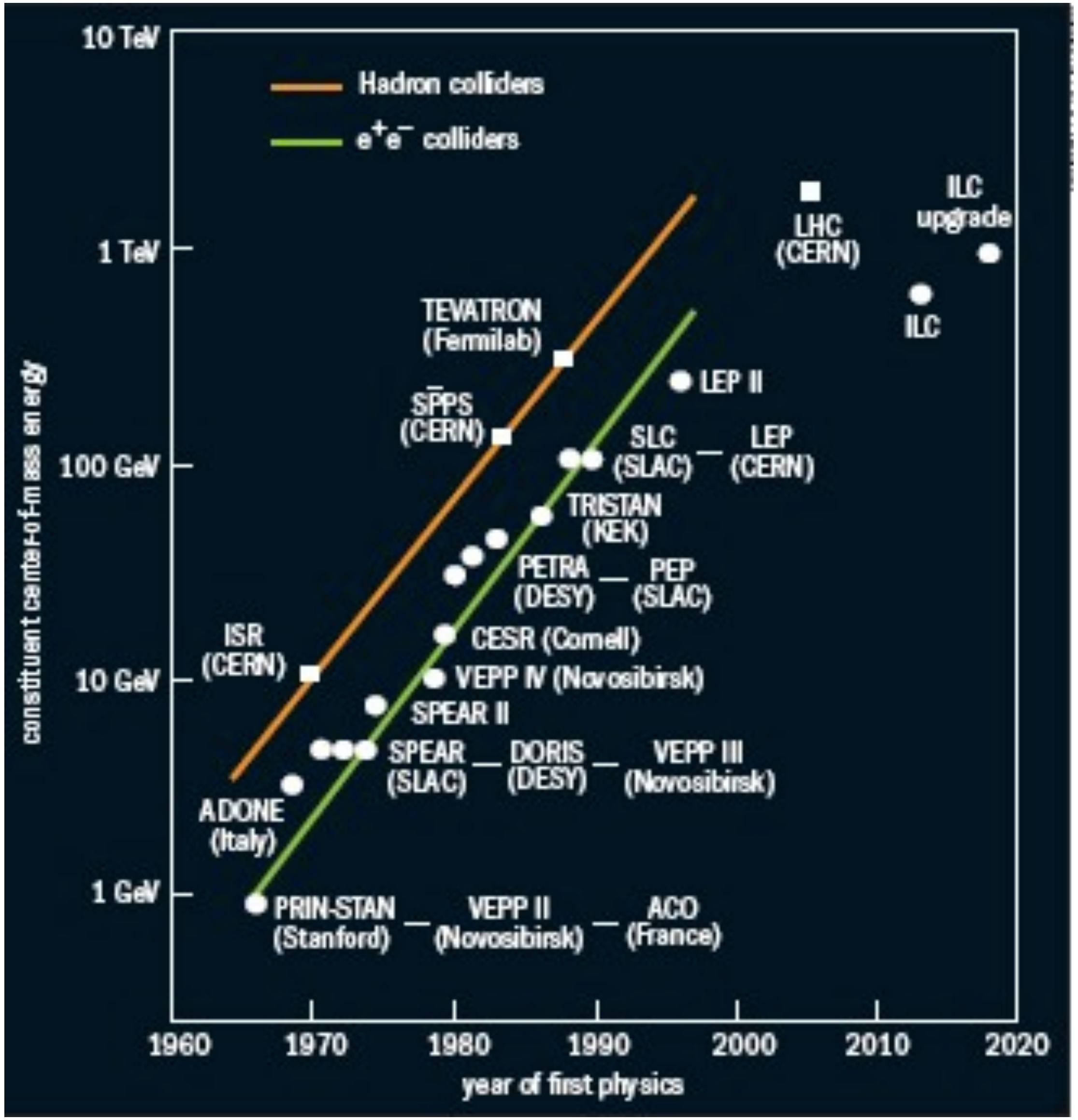


Neutron generator





Why Accelerator-based Sources?
The Livingston Curve of Accelerator Development



- Today some 30,000 particle accelerators operate in the world. Only a small fraction of them are devoted to basic science.
- The market for medical and industrial accelerators currently exceeds $3.5B per year, with a growth rate more than 10% annually.
- All the products that are processed, treated or inspected by particle beams have a collective annual value of more than $500B. US DOE 2010

Neutron Sources: Past, Present, & Future

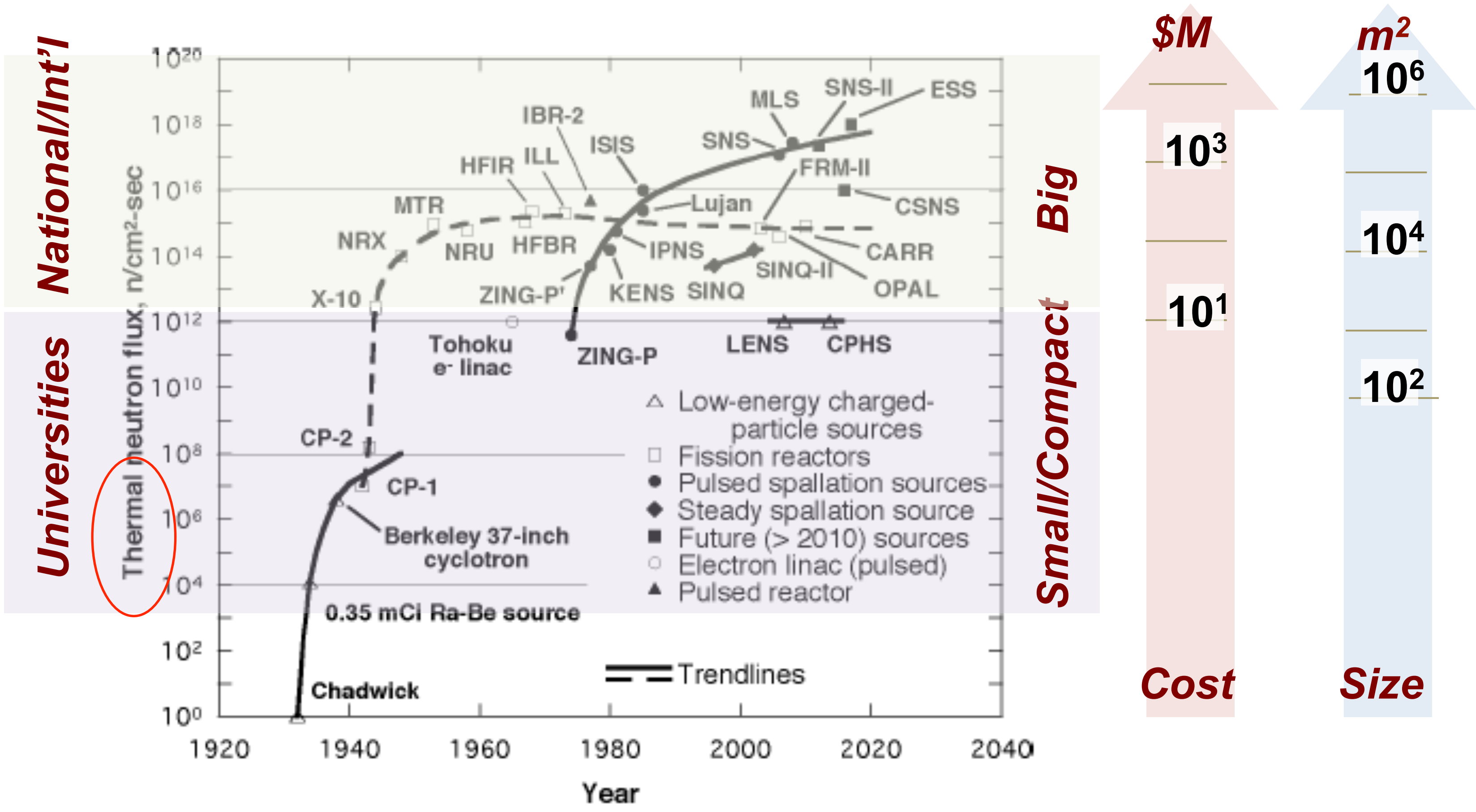
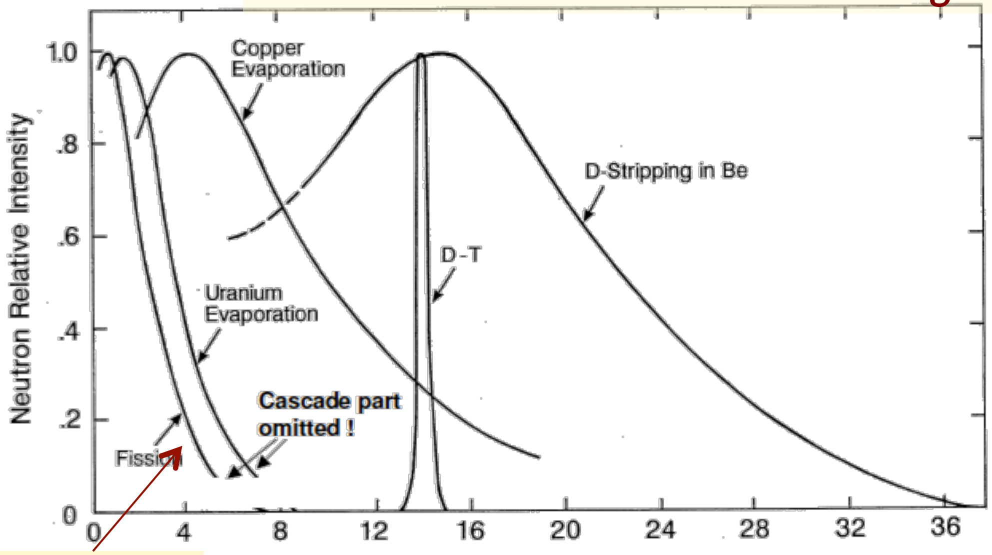


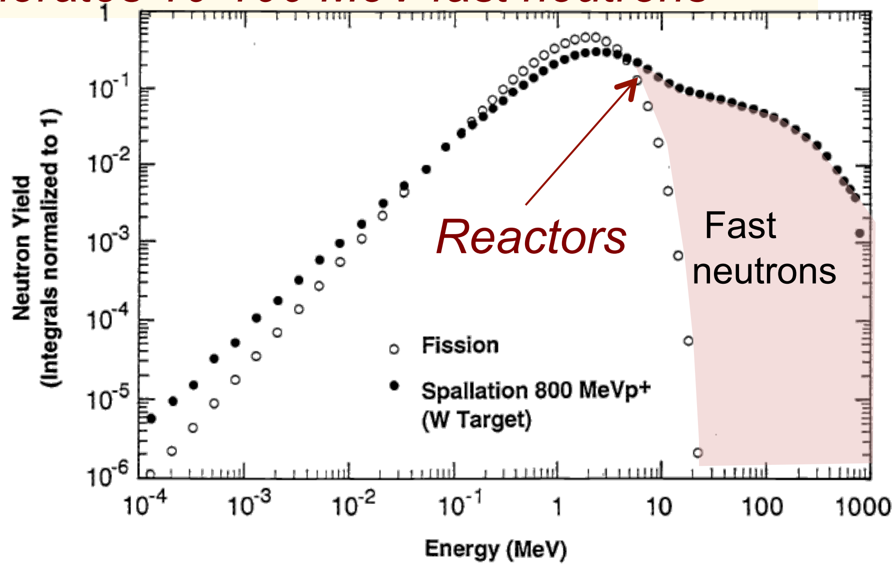
Figure 1. History of development of neutron sources in terms of the effective thermal neutron flux. Carpenter & Lander 2010

This is not the whole story!

Neutron Energy Spectrum & Time Structure

Accelerator-driven sources generates 10-100 MeV fast neutrons

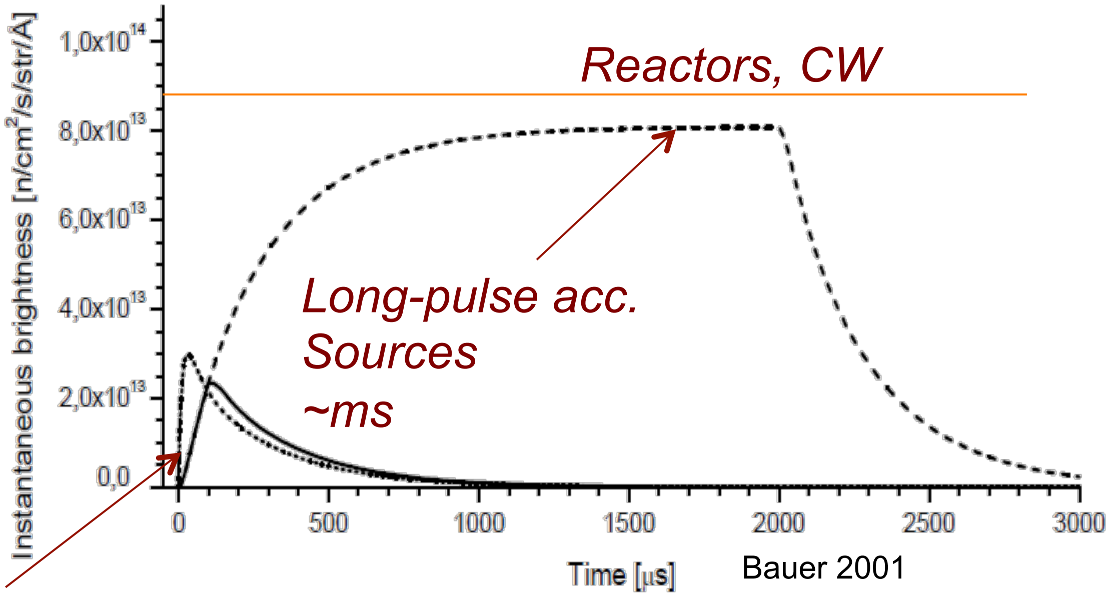




Accelerator-driven sources generate neutrons with

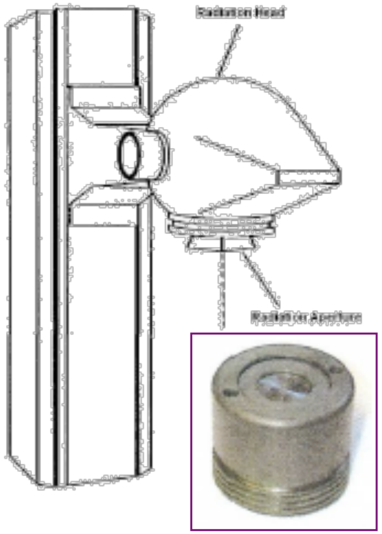
- a wide energy spectrum, providing cold, thermal, epithermal, and fast neutrons
- A distinct time structure from μs to ms

Therefore, accelerator-based sources lend more applications than reactor-based sources.



Compact Accelerator-driven Neutron Sources (CANS)

- Big sources are too expensive, too large, and missions too rigid—not for universities
- Isotopic sources are difficult to safeguard, prone to misuses by mismanagement or by terrorist act
- *CANS appears to have many positive potentials for the future*

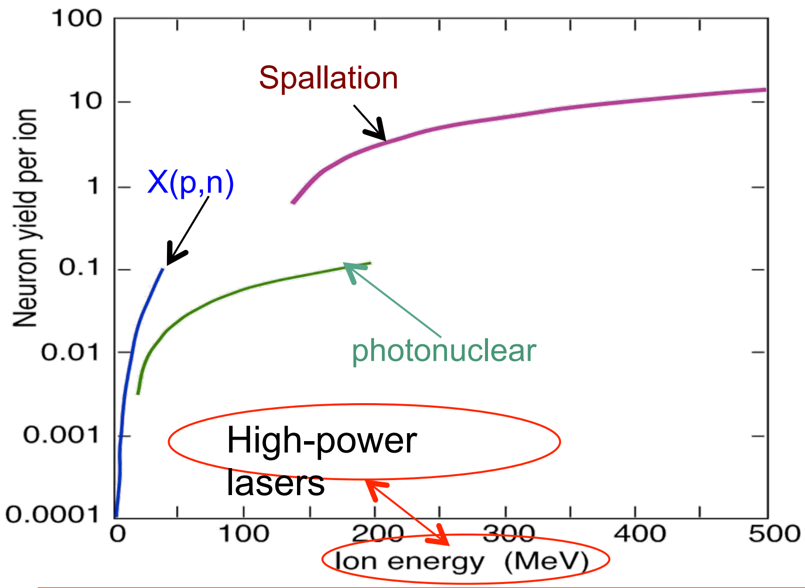


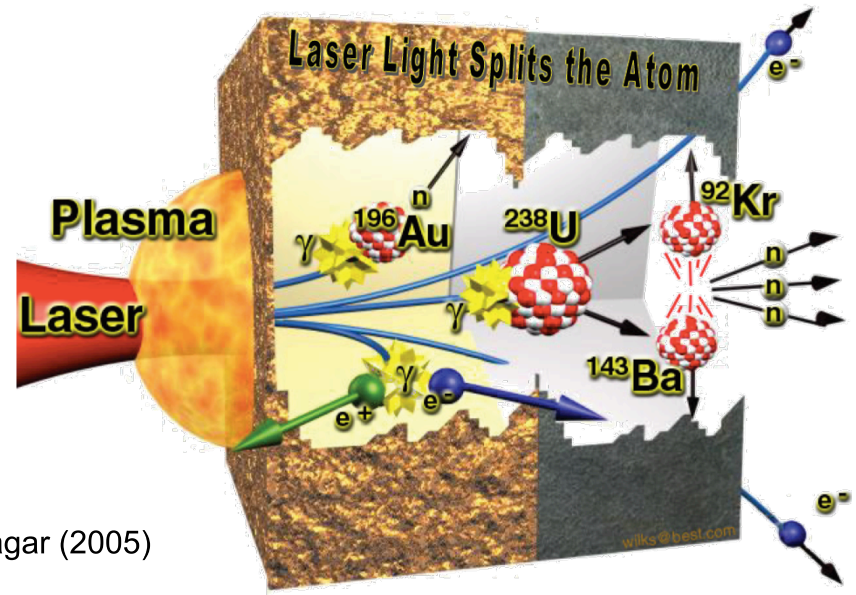
A typical teletherapy machine used in hospitals (left) in which a radioactive CsCl power is contained inside a sealed holder (~12mm in diameter) (middle). In 1987 a Cs-137 source from an abandoned teletherapy device was dispersed in Goiania, Brazil, causing serious contamination and environmental problems (right).

(2005)

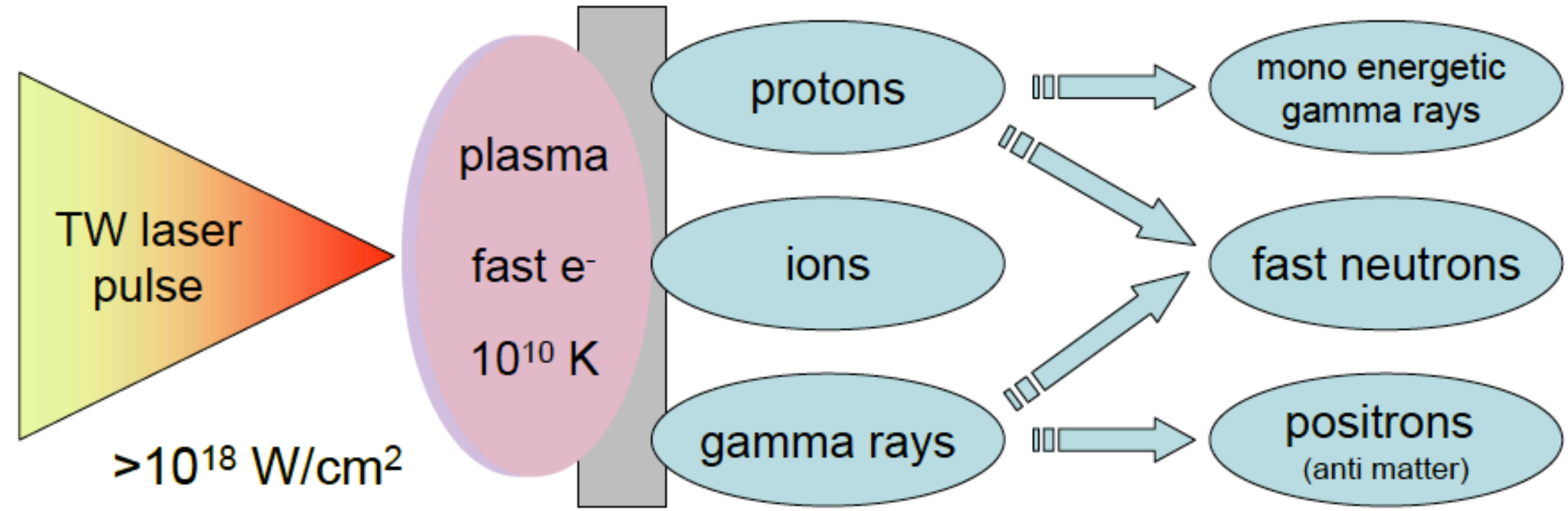
(2012)

Laser-generated 'Table-Top' Neutron Sources

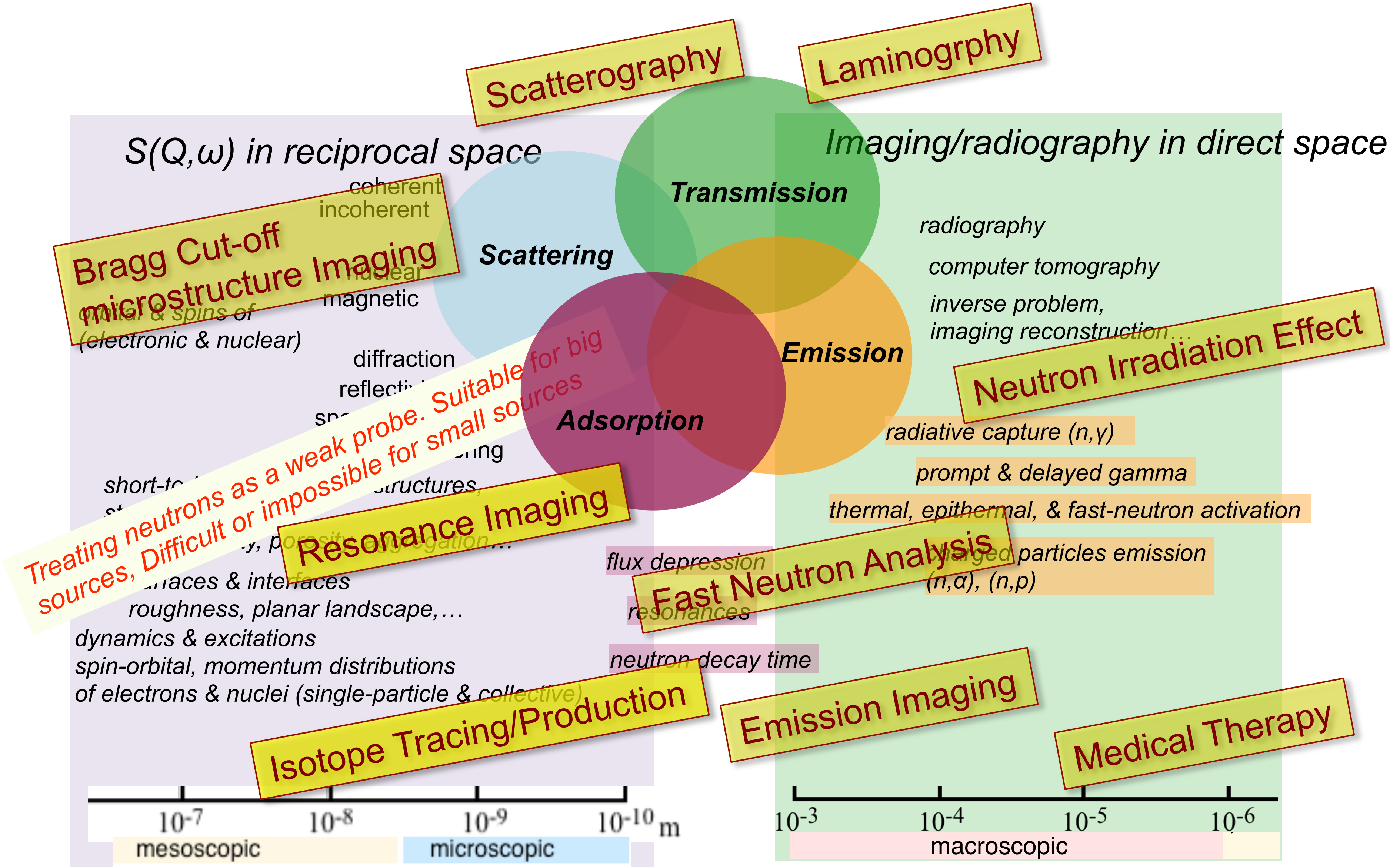




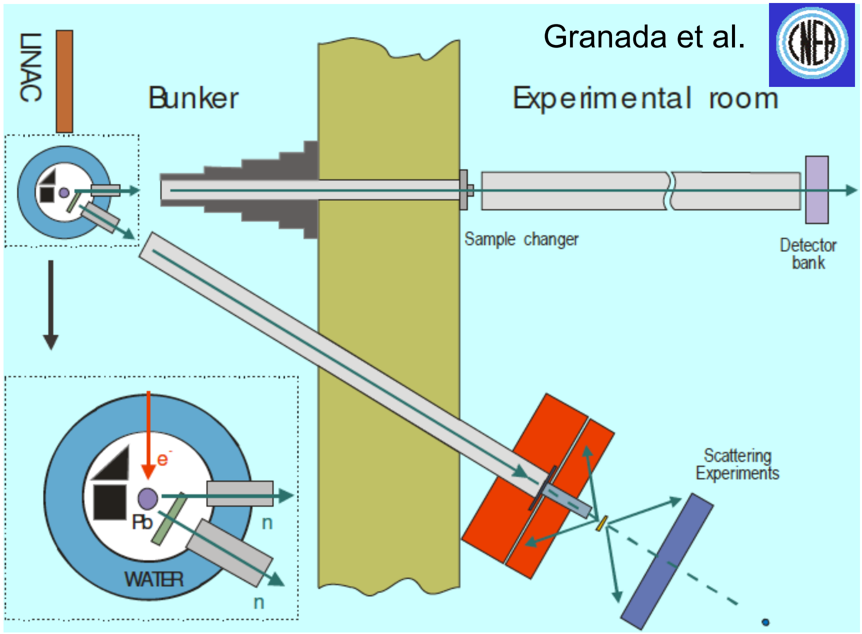
Zagar (2005)

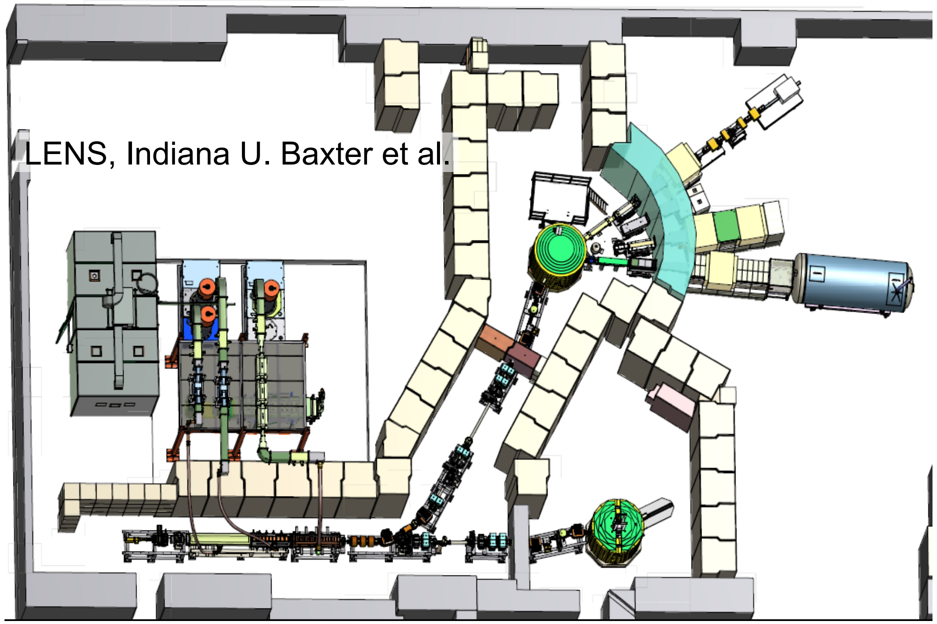


Applications of CANS: By Exploiting the Neutron Properties



Existing CANS: A Long History & A Productive Feast





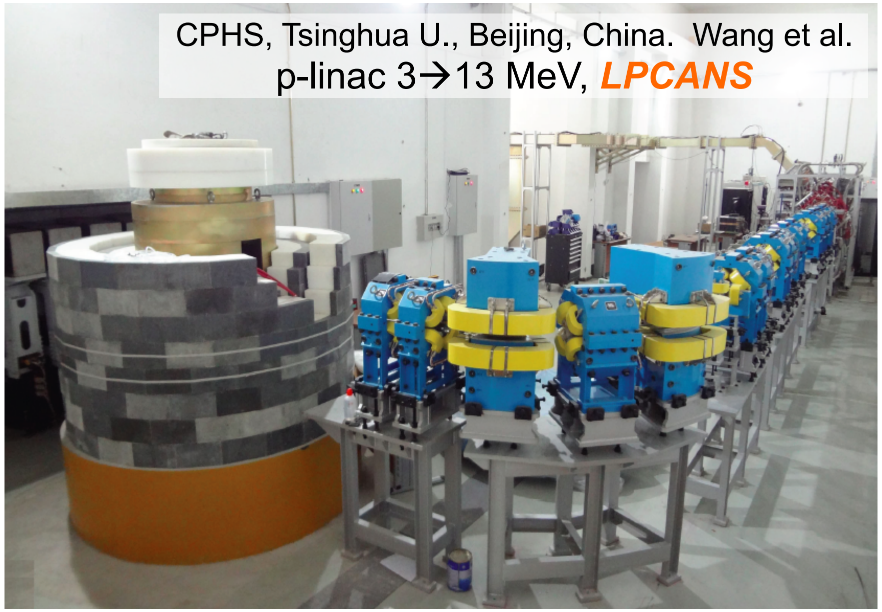
Bariloche e-Linac NS, Argentina
e-linac 25 MeV, ***SPCANS***…….45 years

HUNS: Hokkaido e-Linac NS, Hokkaido, Japan
e-linac 45 MeV, ***SPCANS***…….40 years

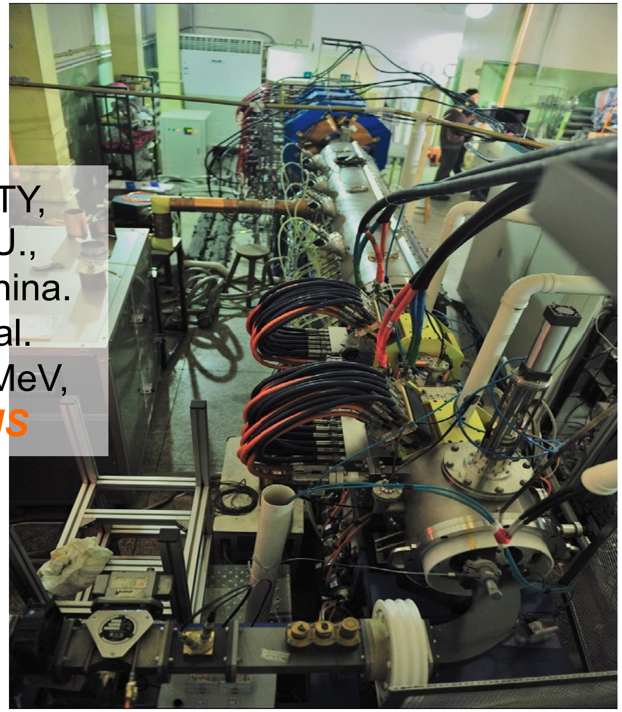
LENS: Indiana U, USA
p-linac 13 MeV, ***LPCANS***…….9 years

Diffraction, SANS, reflectometry, radiography/imaging, DINS, novel moderator & instrumentation R&D; education & training

Newly Established CANS: Commissioning (2013)



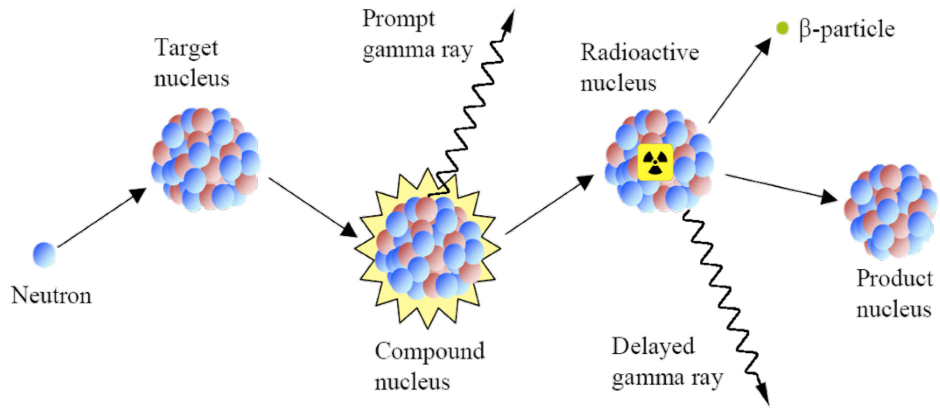
PKUNIFTY, Peking U., Beijing, China. Guo et al. d-linac 2 MeV, *LPCANS*



SANS, radiography/imaging; Education & training; Industrial applications

Imaging & Radiography: Beyond Conventional Approaches (1)

Combine tomography with thermal-neutron-induced γ-ray imaging (PGA-CT):
Allow 3D elemental analysis



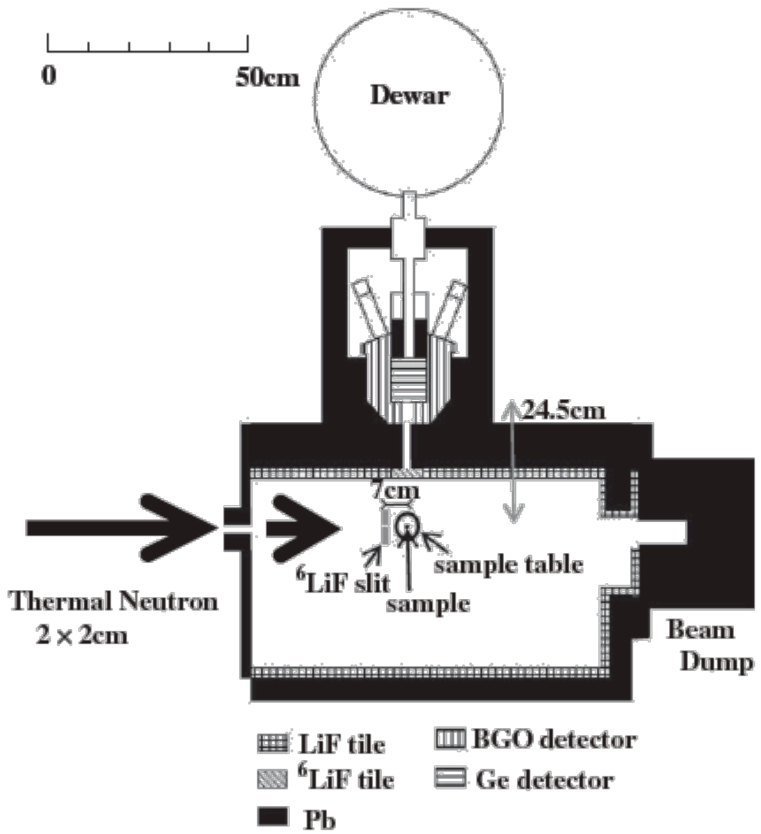


Fig. 1. Schematic view of experimental setup.

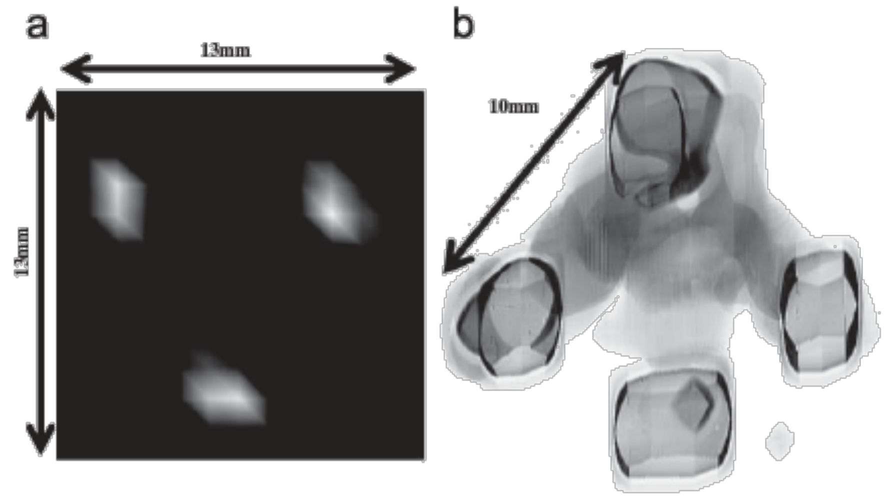
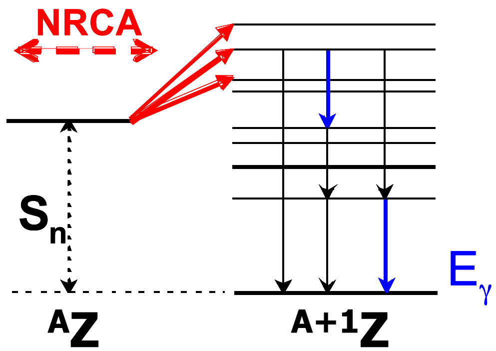


Fig. 5. The reconstruction images for a Cd sample in the form of a three-sided pyramid of 1 cm using the computerized tomography program "NIPPON". (a) A slice figure on the bottom of the sample in the X–Z plane. (b) A 3-D elemental image made by accumulations of slice figures.

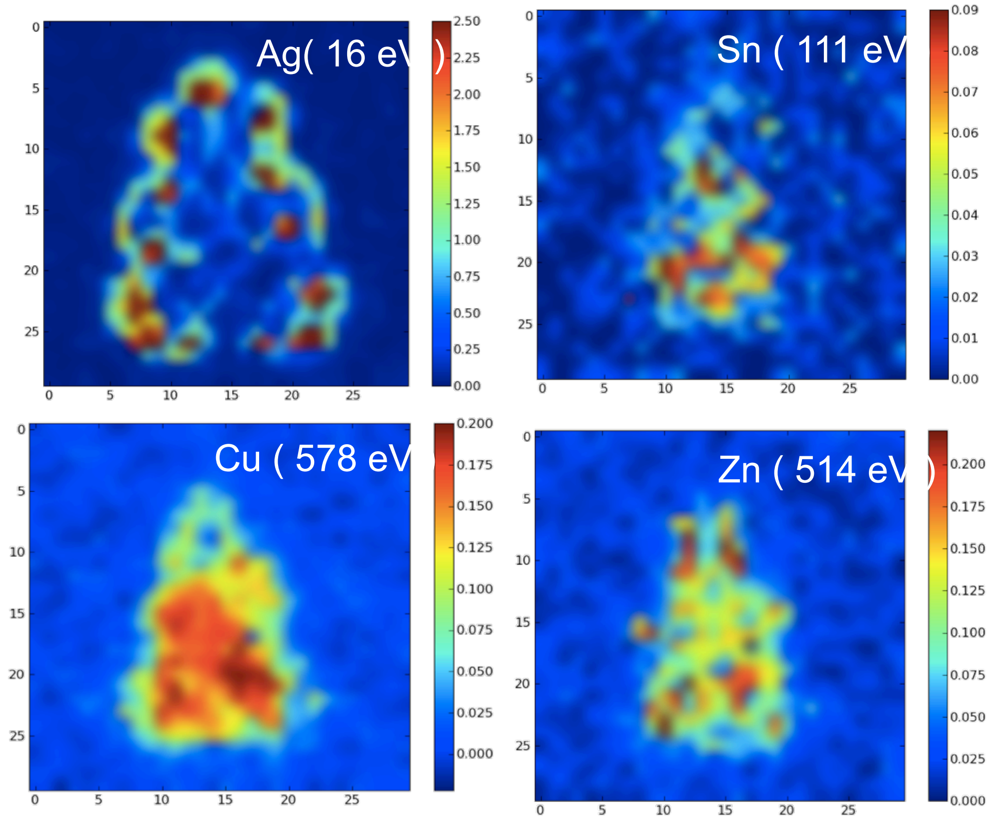
Segawa 2009

Imaging & Radiography: Beyond Conventional Approaches (2)

Combine imaging with epithermal neutron resonance capture analysis (NRCA):
Allow elemental analysis, significant to archaeometry: high sensitivity to Cu, Sn Zn, As, Sb, Ag, Au, Pb,…



Original belt mount
Hungarian National Museum, Budapest

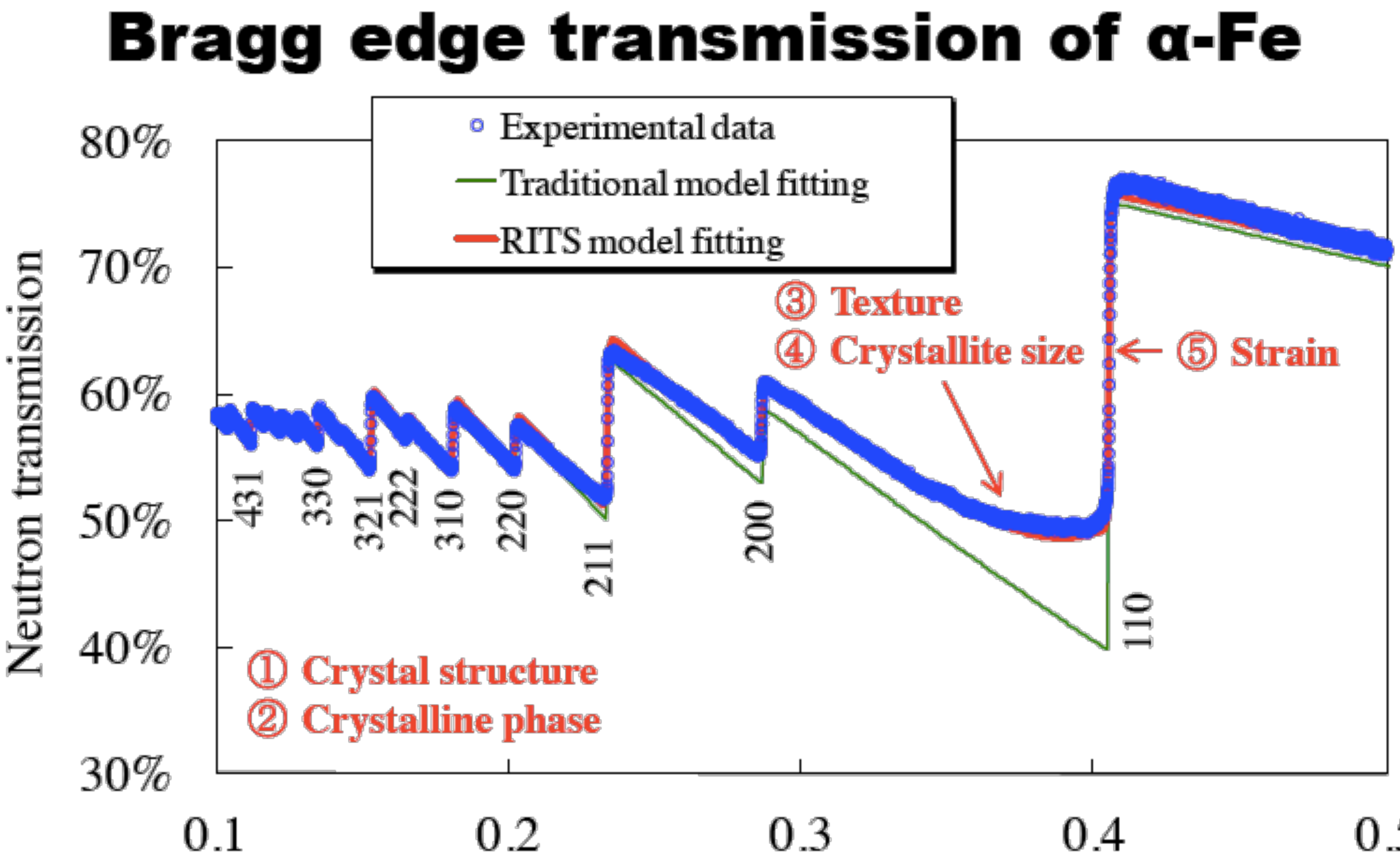


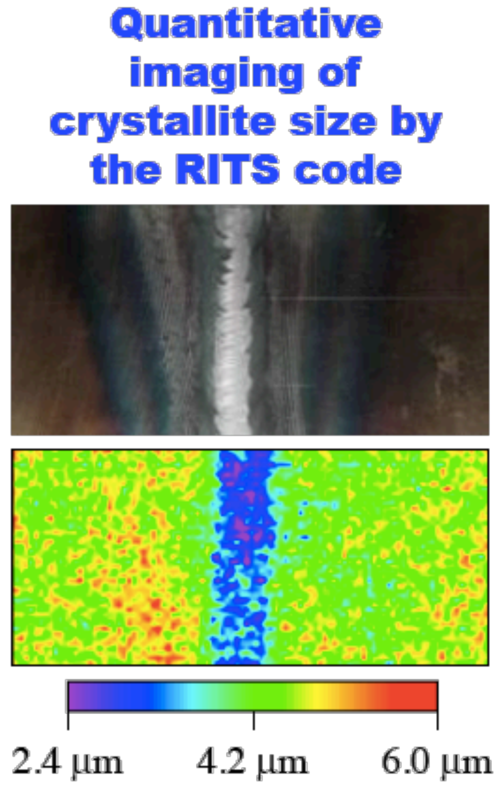
Andreani 2012

Imaging & Radiography: Beyond Conventional Approaches (3)

Combine imaging with crystal diffraction: Rietveld imaging transmission spectra (RITS)

Allow concurrent analysis of crystal structures, crystalline phases, crystallite sizes, texture, and strain



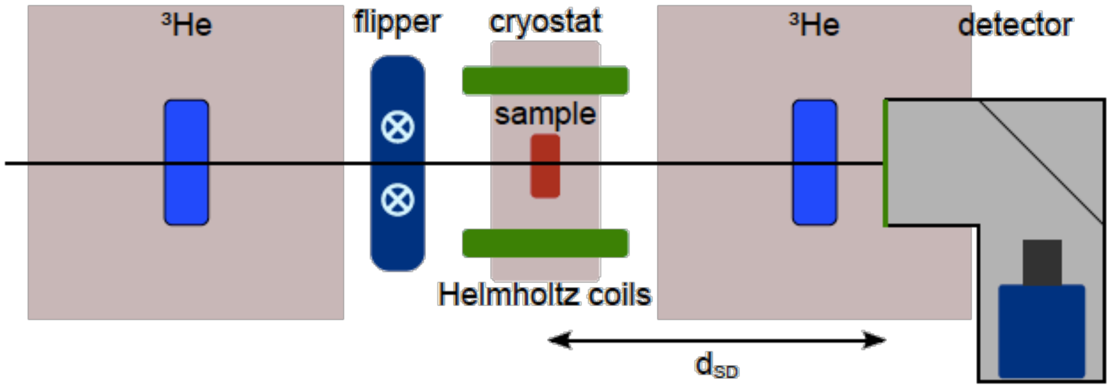


Sato 2011

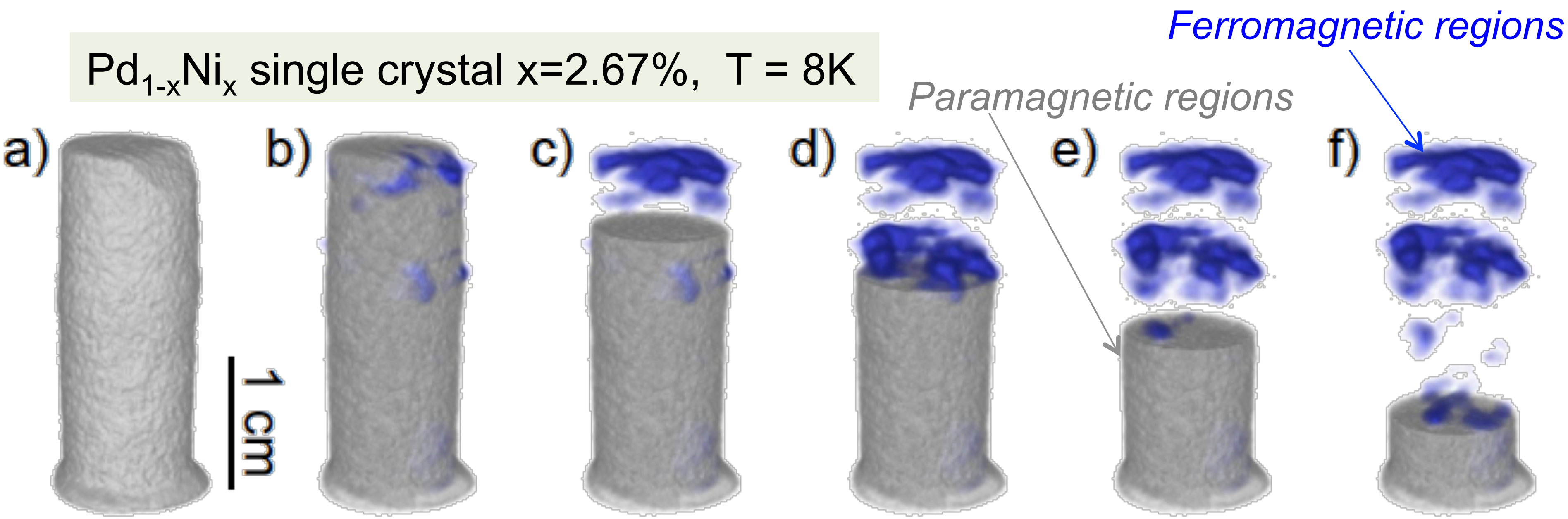
Magnetic Structures: Beyond Conventional Approaches (4)

Combine imaging with polarization analysis of magnetic diffraction using polarized neutrons

Allow fundamental studies of quantum criticality, magnetic inhomogeneity in single crystals by depolarization imaging



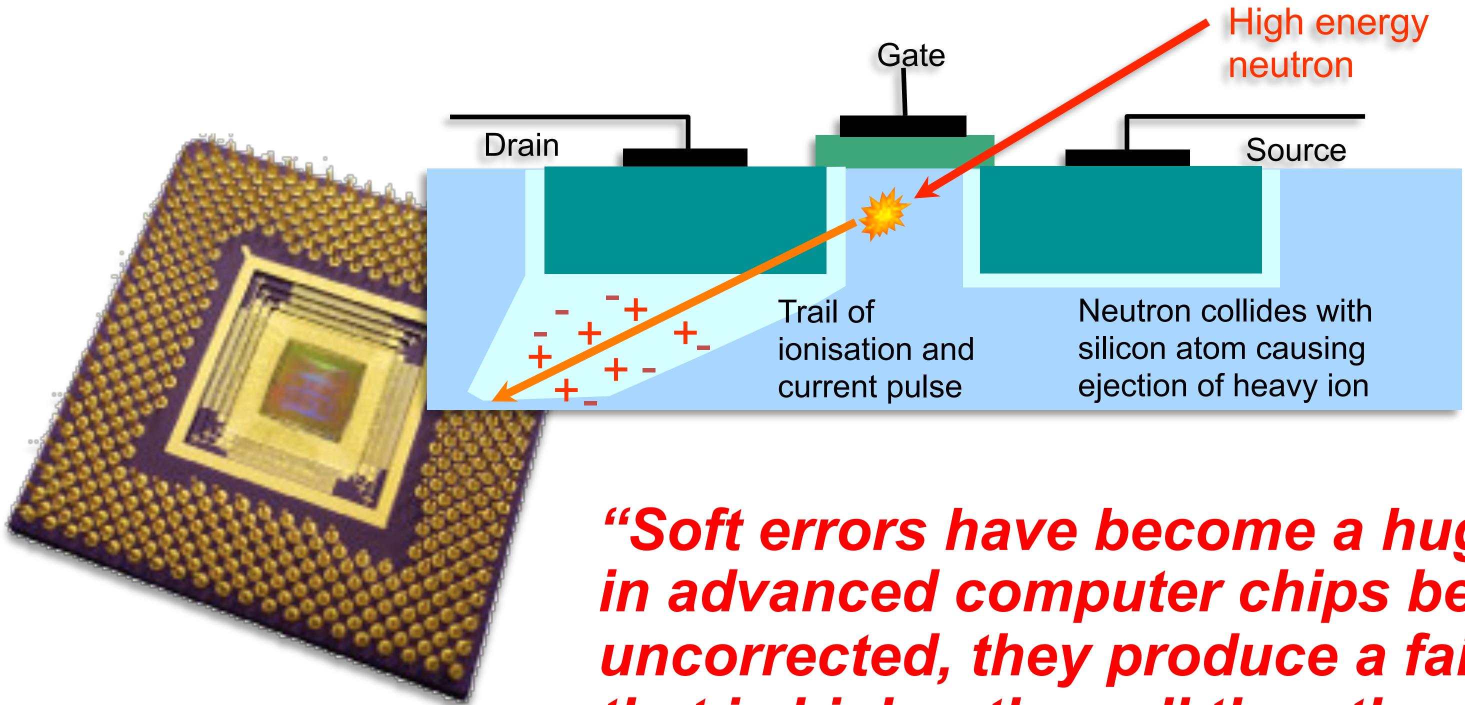
$Pd_{1-x}Ni_x$ single crystal x=2.67%, T = 8K



Schulz 2010

Neutron Impact on Industry and Life

Single Event Effects (SEE): A single energetic particle (neutron) strikes sensitive regions of an electronic device, e.g., logic or support circuitry, memory cells, registers, etc., disrupting its normal function, usually causing non-destructive soft errors.



"Soft errors have become a huge concern in advanced computer chips because, uncorrected, they produce a failure rate that is higher than all the other reliability mechanisms combined!"

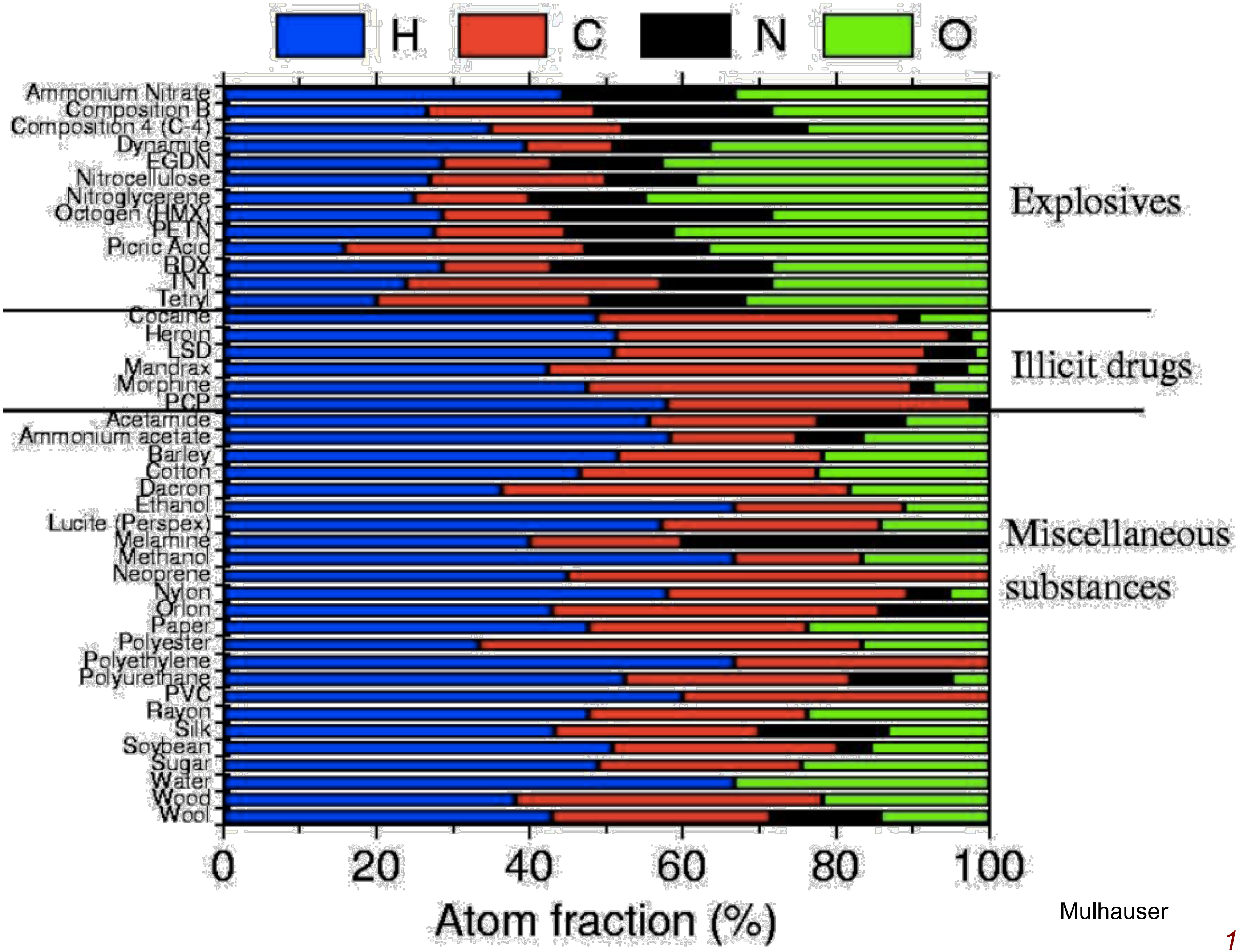
.......R. Baumann, IEEE-TDMR, 2005

Frost 2011

Desirable capabilities

- ✧ Remote detection
- ✧ Non-intrusive
- ✧ High sensitivity (chemical density, 3D volumetric rendering)
- ✧ Materials specific (precise, minimize false alarms)
- ✧ Rapid
- ✧ Flexible (portable, on-site deployment,…)
- ✧ Automatic

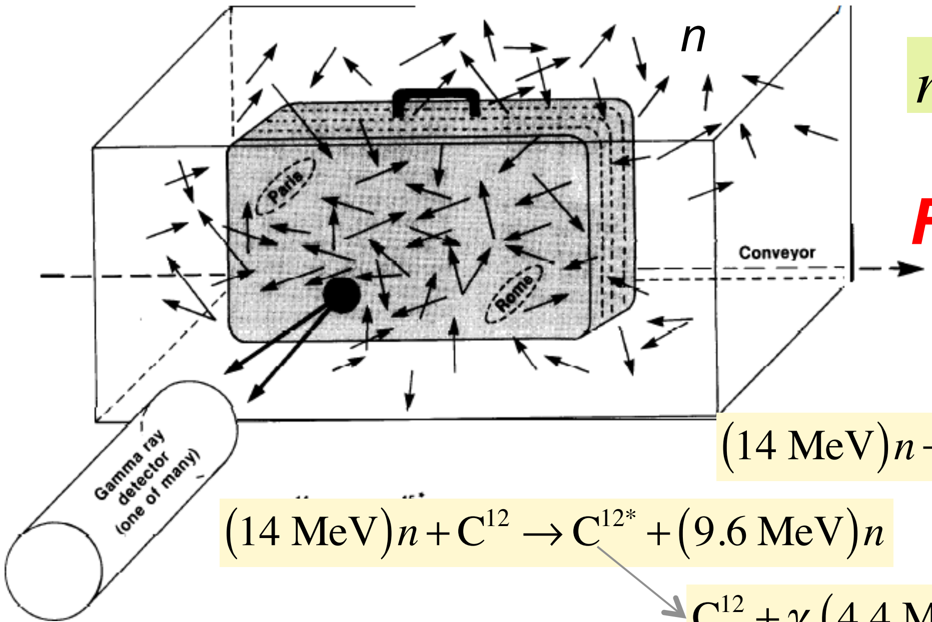
Chemical Composition of Different Materials



Mulhauser

"Neutron in Gamma Out" Methods (1)

Thermal Neutron Analysis (TNA): In TNA the object is irradiated by slow (thermal) neutrons, which produce gamma-rays in reactions of radiative capture with the nuclei of chemical elements constituting ES. e.g. N: 10.8 MeV H: hydrogen 2.23 MeV Cl: 7.50 and 6.11 MeV, etc.
Fast Neutron Analysis (FNA): The object is irradiated with a continuous flux of fast neutrons with energy above 8 MeV, which produce characteristic gamma-rays in inelastic scattering reactions with nuclei of C: 4.44, O: 6.13,.. N: 5.1 MeV. Detection of these secondary gamma-rays provides information about relative concentrations of carbon, oxygen and nitrogen in molecules of the inspected substance.
Neutron Resonance Attenuation (NRA): A neutron radiography technique measuring the areal density (density times thickness) of elements present in the interrogated object.



TNA

$$n + \mathrm{N}^{14} \rightarrow \mathrm{N}^{16*} \rightarrow \mathrm{N}^{15} + \gamma\,(10.8\ \mathrm{MeV})$$

FNA

$$(14\ \mathrm{MeV})\,n + \mathrm{N}^{14} \rightarrow \mathrm{N}^{14*} + (8.9\ \mathrm{MeV})\,n, \quad \mathrm{N}^{14*} \rightarrow \mathrm{N}^{14} + \gamma\,(5.1\ \mathrm{MeV})$$

$$(14\ \mathrm{MeV})\,n + \mathrm{O}^{16} \rightarrow \mathrm{O}^{16*} + (7.9\ \mathrm{MeV})\,n, \quad \mathrm{O}^{16*} \rightarrow \mathrm{O}^{16} + \gamma\,(6.1\ \mathrm{MeV})$$

$$(14\ \mathrm{MeV})\,n + \mathrm{C}^{12} \rightarrow \mathrm{C}^{12*} + (9.6\ \mathrm{MeV})\,n, \quad \mathrm{C}^{12*} \rightarrow \mathrm{C}^{12} + \gamma\,(4.4\ \mathrm{MeV})$$

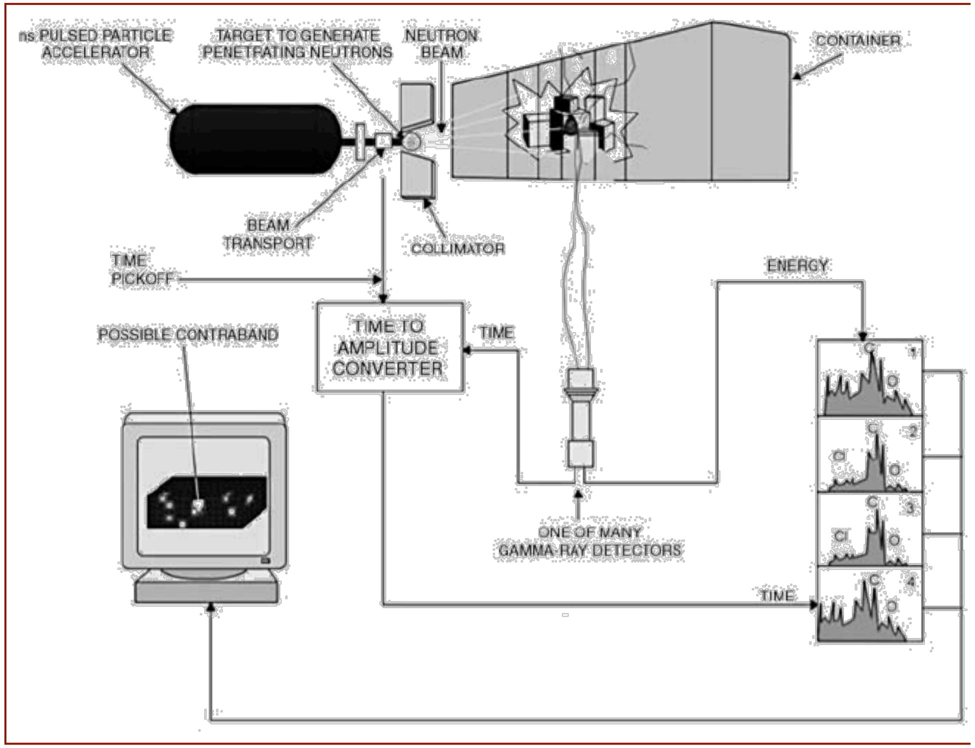
Grodzine 1990; Schubert 2006

"Neutron in Gamma Out" Methods (2)

Pulsed Fast Neutron Analysis (PFNA): Use pulsed neutron flux (with pulse duration of several nanoseconds) to irradiate the inspected object. This allows one to use time of flight information to determine the location of the ES inside the inspected volume. By using collimators for the neutron beam one can get a 3D distribution of carbon, oxygen and nitrogen in the investigated object.

Pulsed Fast and Thermal Neutron Analysis (PFTNA): PFTNA is a combination FNA and TNA.

Nanosecond Neutron Analysis / Associated Particles Technique (NNA/APT): Use d(t,α)n to produce fast neutrons in portable neutron generators, mono-energetic neutrons (E = 14 MeV) and α-particles (E = 3 MeV) are emitted simultaneously in opposite directions. Tag *n* with α to discriminate secondary γ. Background γ-rays that are not correlated in time with "tagged" neutrons are rejected by the data acquisition system. Use of position sensitivity of the α-detector and time-of-flight analysis allow one to obtain 2D spatial distribution of chemical elements in the examined object.

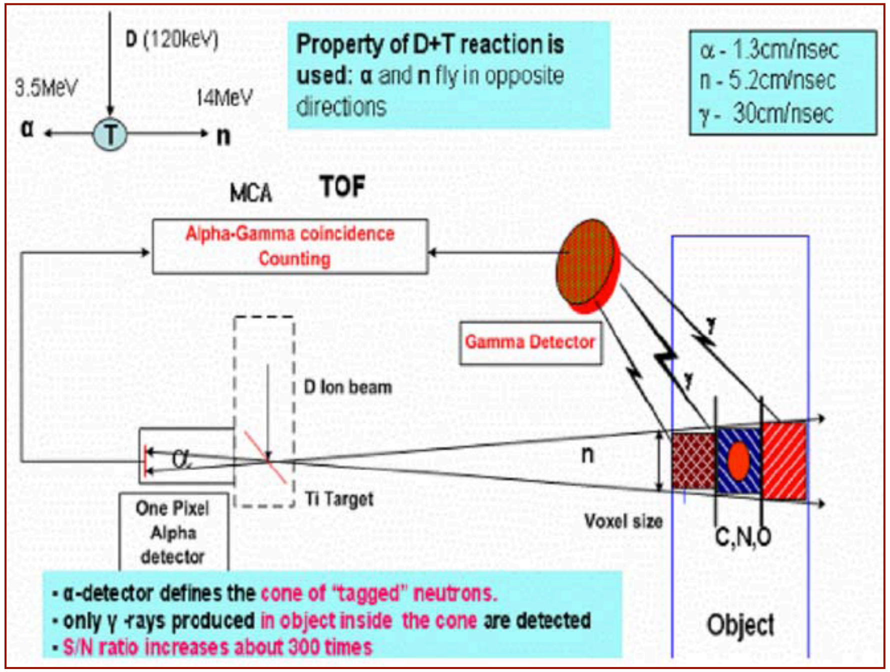


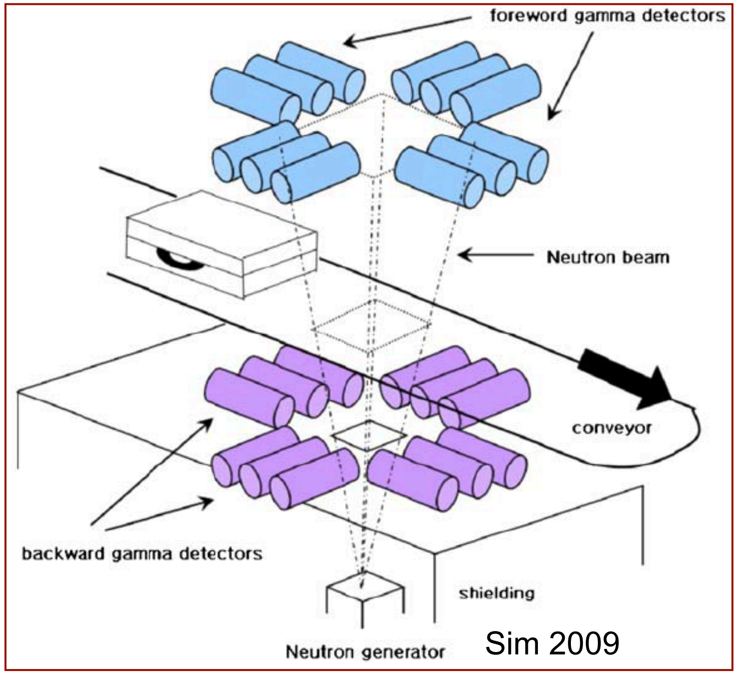
PFNA

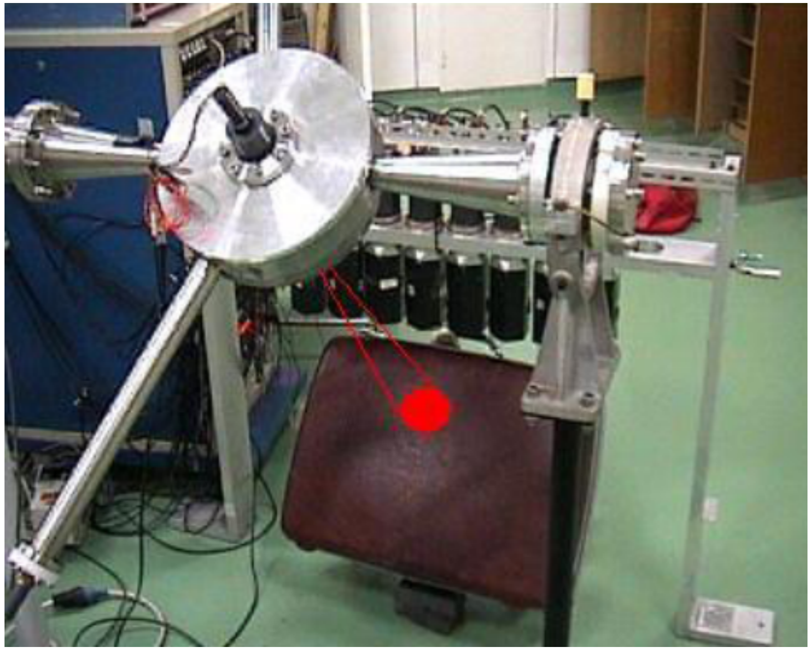
Gozani 2005

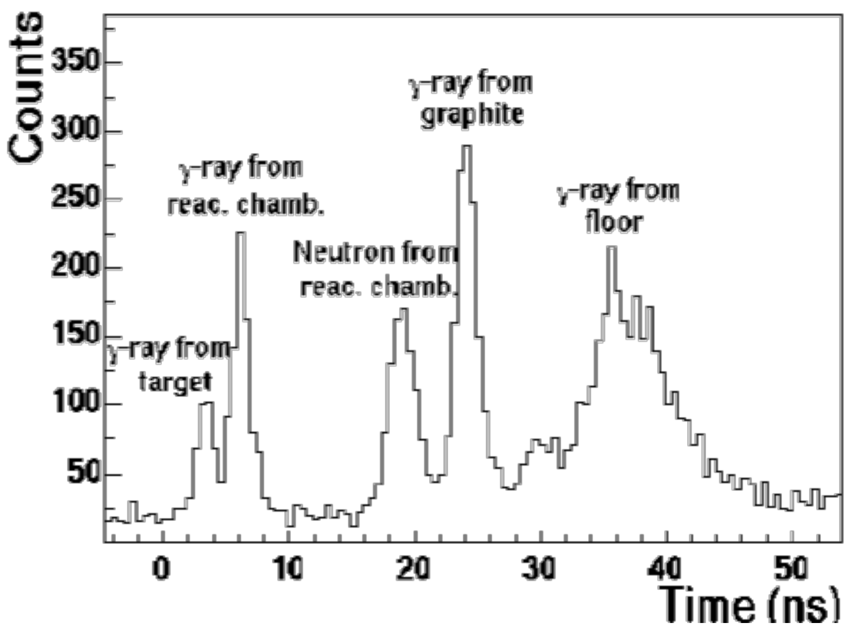
Associated-Particle Imaging (API)

Nanosecond Neutron Analysis / Associated Particles Technique (NNA/ APT): Use d(t,α)n to produce fast neutrons in portable neutron generators, mono-energetic neutrons (E = 14 MeV) and α-particles (E = 3 MeV) are emitted simultaneously in opposite directions. Tag *n* with alpha to discriminate secondary γ. Background γ-rays that are not correlated in time with “tagged” neutrons are rejected by the data acquisition system. Use of position sensitivity of the γ-detector and time-of-flight analysis allow one to obtain 2D spatial distribution of chemical elements in the examined object.








Counts
350
300
250
200
150
100
50
γ-ray from
target
γ-ray from
reac. chamb.
Neutron from
reac. chamb.
γ-ray from
graphite
γ-ray from
floor
0
10
20
30
40
50
Time (ns)

Mulhauser

First Commercial Scanner – Nuctech AC6015XN

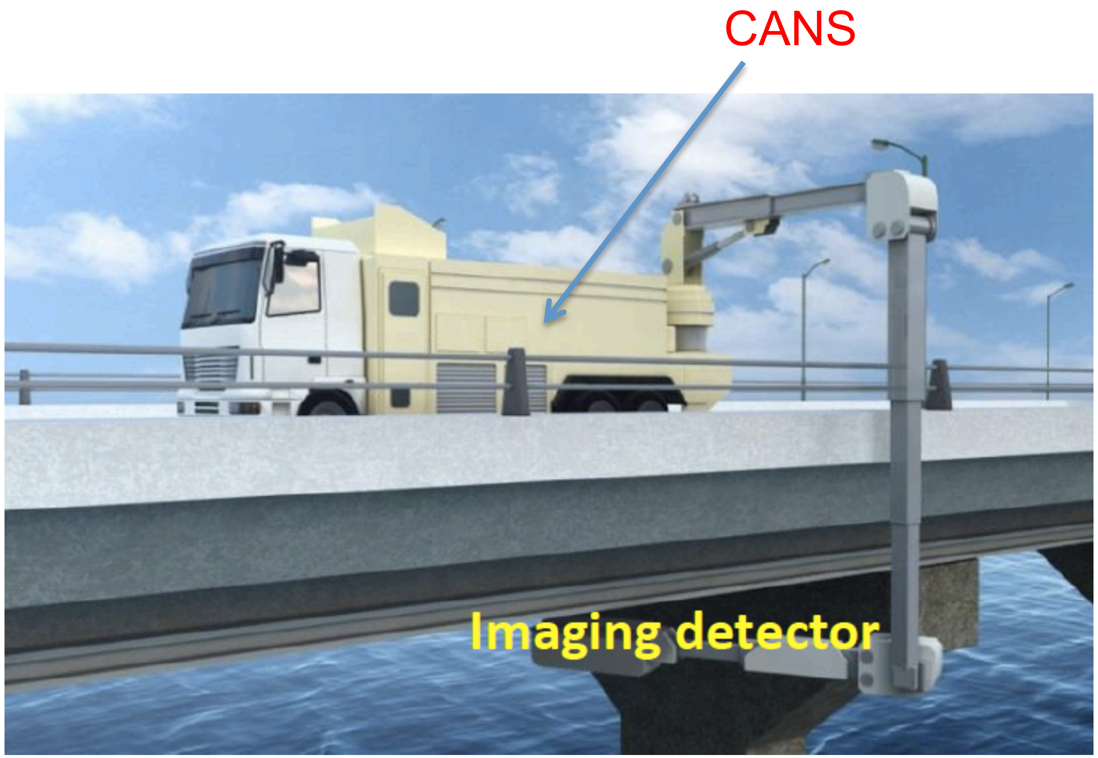
Needing improvement in order to be practical

Landmine Detection: An Ongoing Effort

Mulhauser

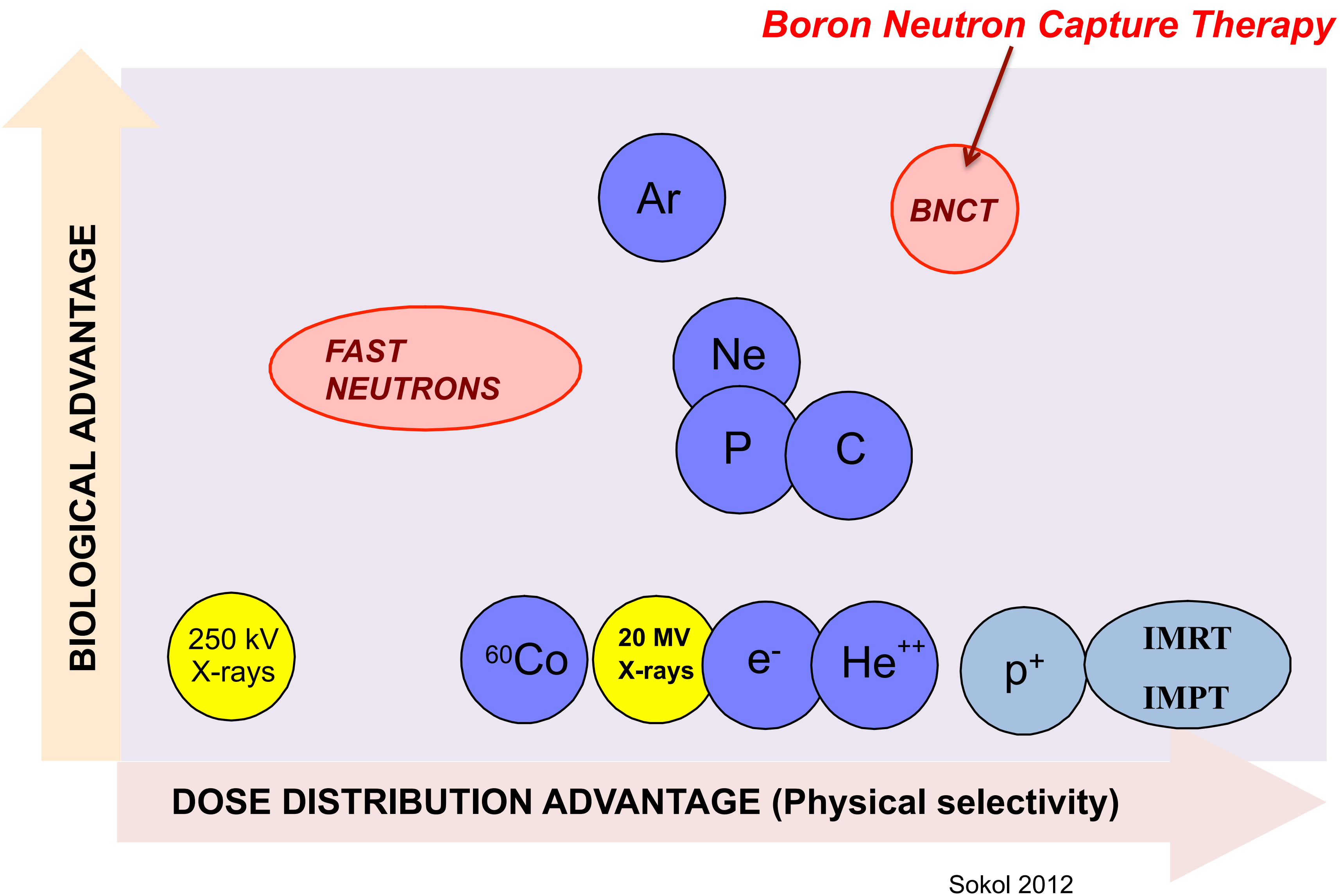
Civil Engineering: Inspection of Large Infrastructure

A Goal to be Fulfilled: Neutron Interrogation Using CANS, To Complement Other Methods

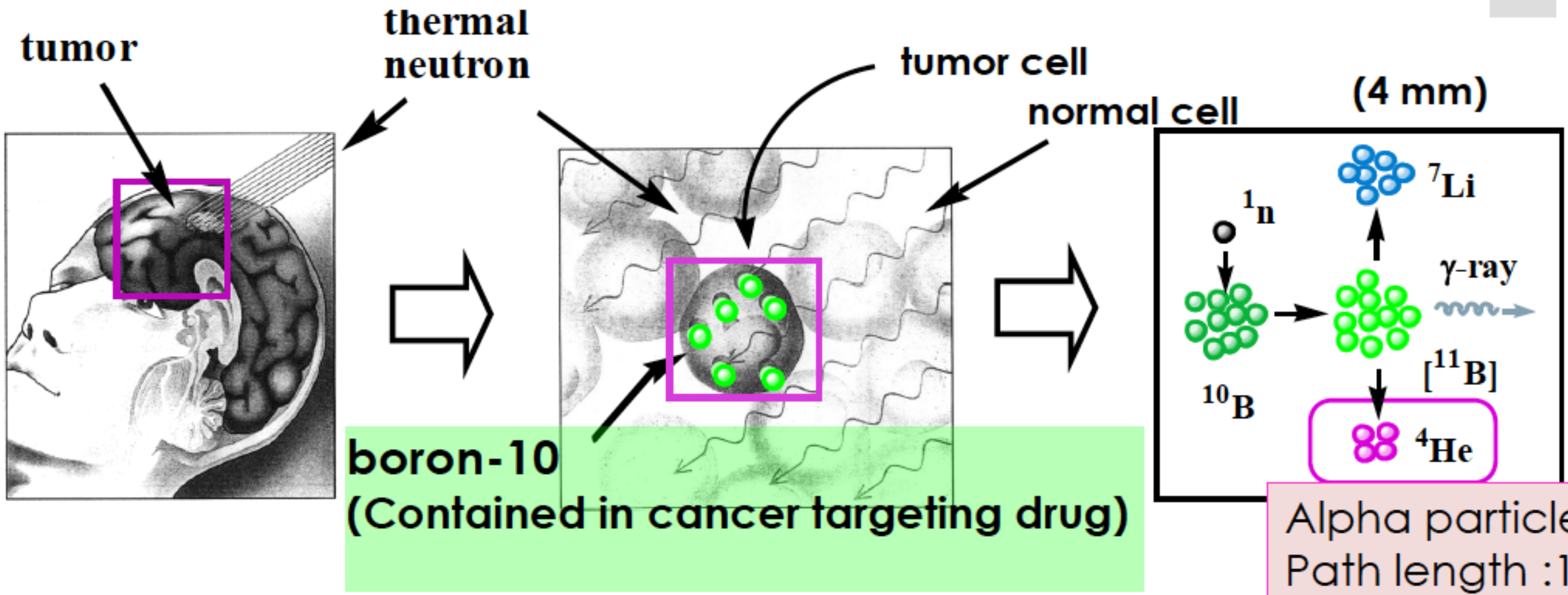


Otake

Neutron Therapy: Superior Biological advantage & Selectivity



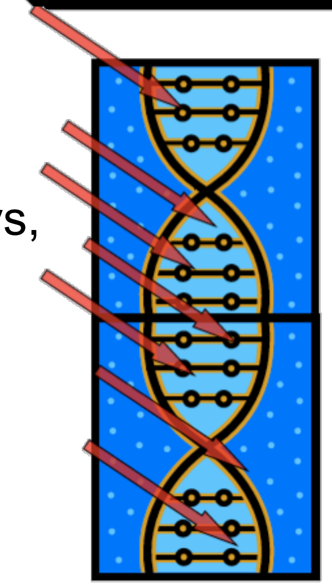
Sokol 2012

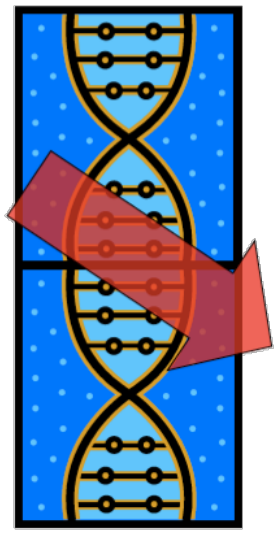


Alpha particle Path length :10 micron

$$^{10}B + {}^{1}n \rightarrow [{}^{11}B] \rightarrow {}^{7}Li + {}^{4}He + 2.79\ MeV$$

X-rays, ϒ-rays, LE protons





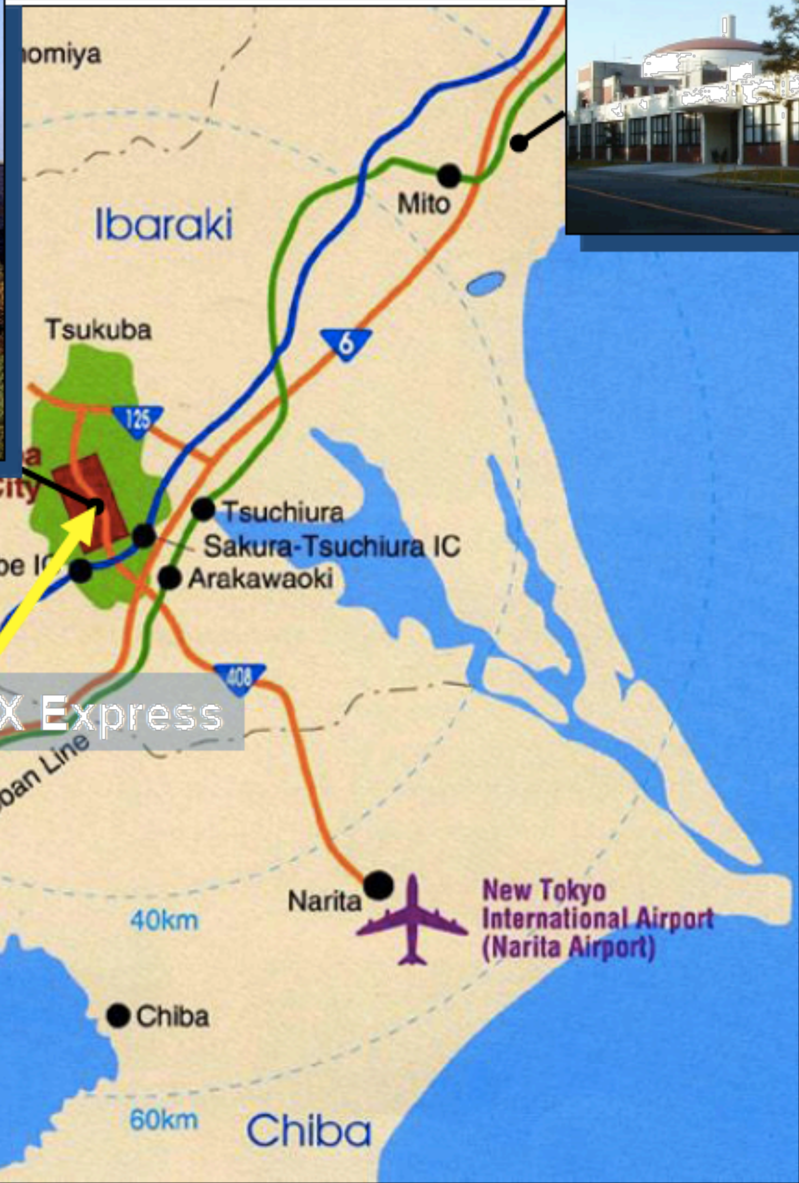
α particles & ^{7}Li nuclei from *boron neutron capture therapy* cut both DNA strands of the tumor cells

Matsumura

UNIVERISTY OF TSUKUBA BNCT GROUP

Tsukuba University Hospital

Proton Medical Resarch Center



JRR-4
at Tokai

Weekly Asahi, Special Issue on new treatment

Modalities (0ct,2010) issued on top page

Matsumura

Sample cases of BNCT Treatment (High effectiveness & preservatoin of normal tissue)

Prof.Kato,Osaka University

Recurrent Parotid Cancer

Pre BNCT

Recurrent tumor after Surgery, Chemotherapy and Radiotherapy. Skin erosion and infection is evident

After 2nd BNCT

Marked shrinkage of the tumor and regeneration of the skin

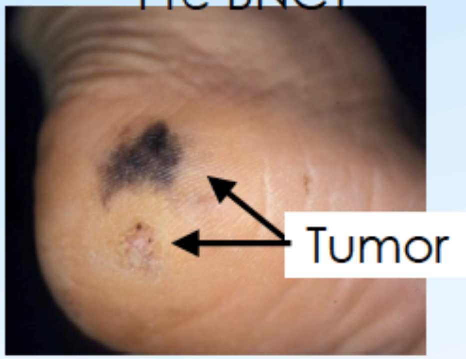
5M after 3rd BNCT

Complete cure by BNCT. The patient was alive 5 yrs without cancer recurrence

Malignant Melanoma at foot

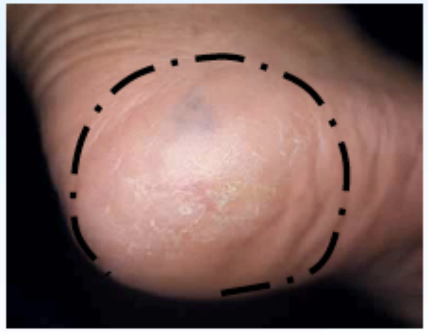
Corutsey of Kawasaki Medical University

Pre BNCT



3M after BNCT

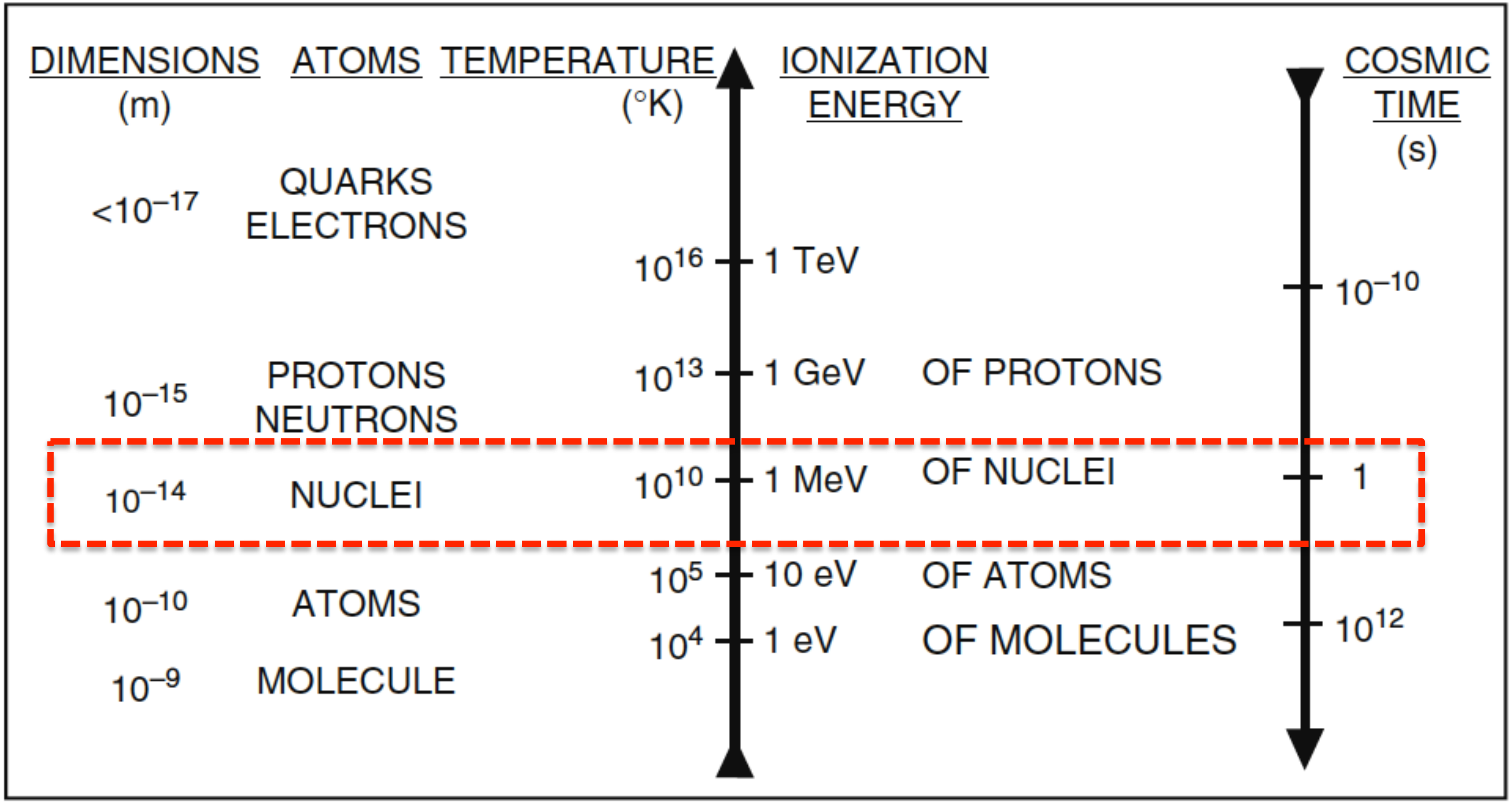
6M after BNCT



Fast Neutron Therapy (FNT)

- Fast neutrons damage cells through high linear-energy-transfer (HLET); kill cancer cells by cutting both cords of the chromosome helix.
- HLET reduces the numbers of treatment by >50% compared with other LLET therapies.
- Under hypoxic conditions (reduced oxygen supply) at the tumor tissue neutrons are more effective than x-rays.
- Currently FNT is only available at a handful facilities in Germany, Russia, USA and South Africa, mainly based on cyclotrons and reactors. Reactors need special beamlines to extract fast neutrons from the reactor core.

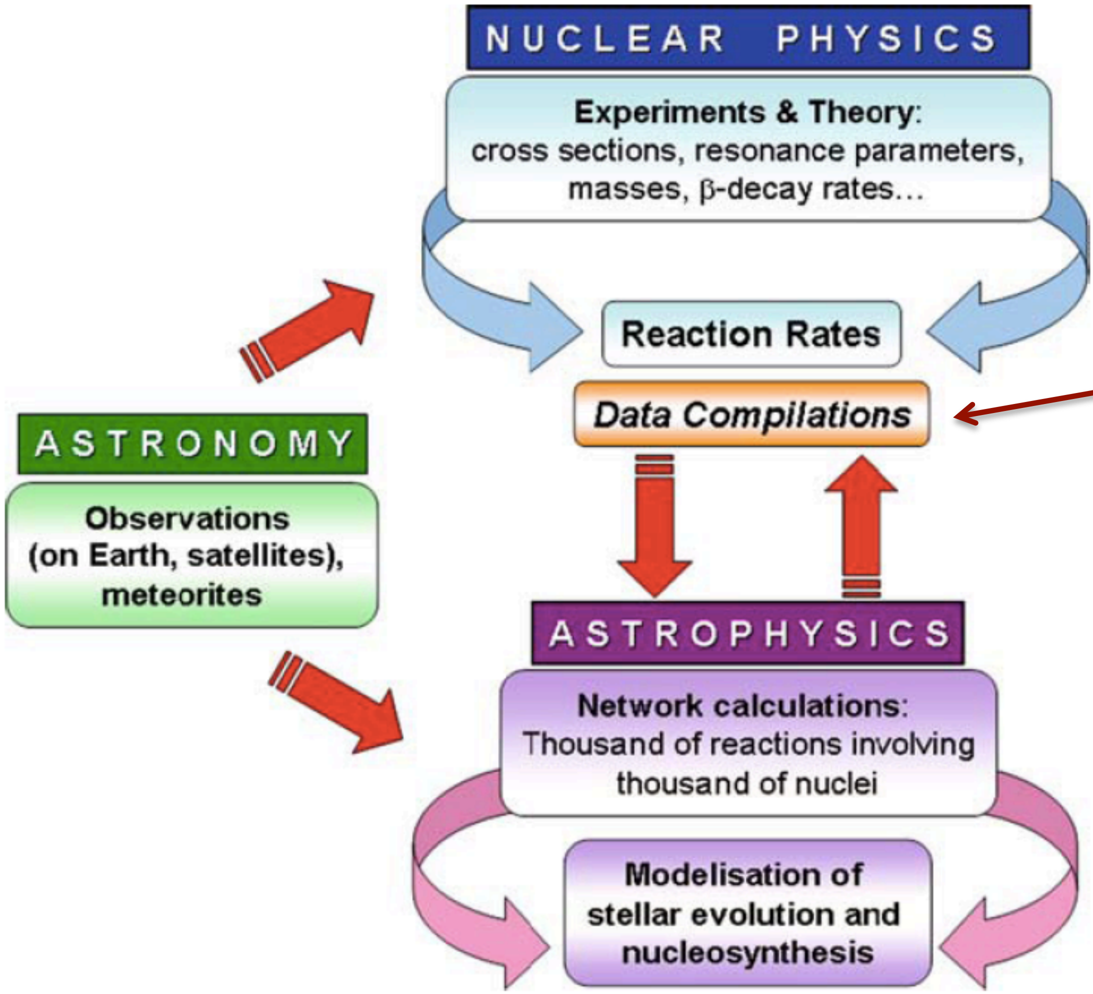
Other Applications: Nuclear Astrophysics, Nuclear Data



CANS provides neutrons of energies (~MeV) comparable to the temperatures of the sun and supernova explosion.

Reciprocity Theorem

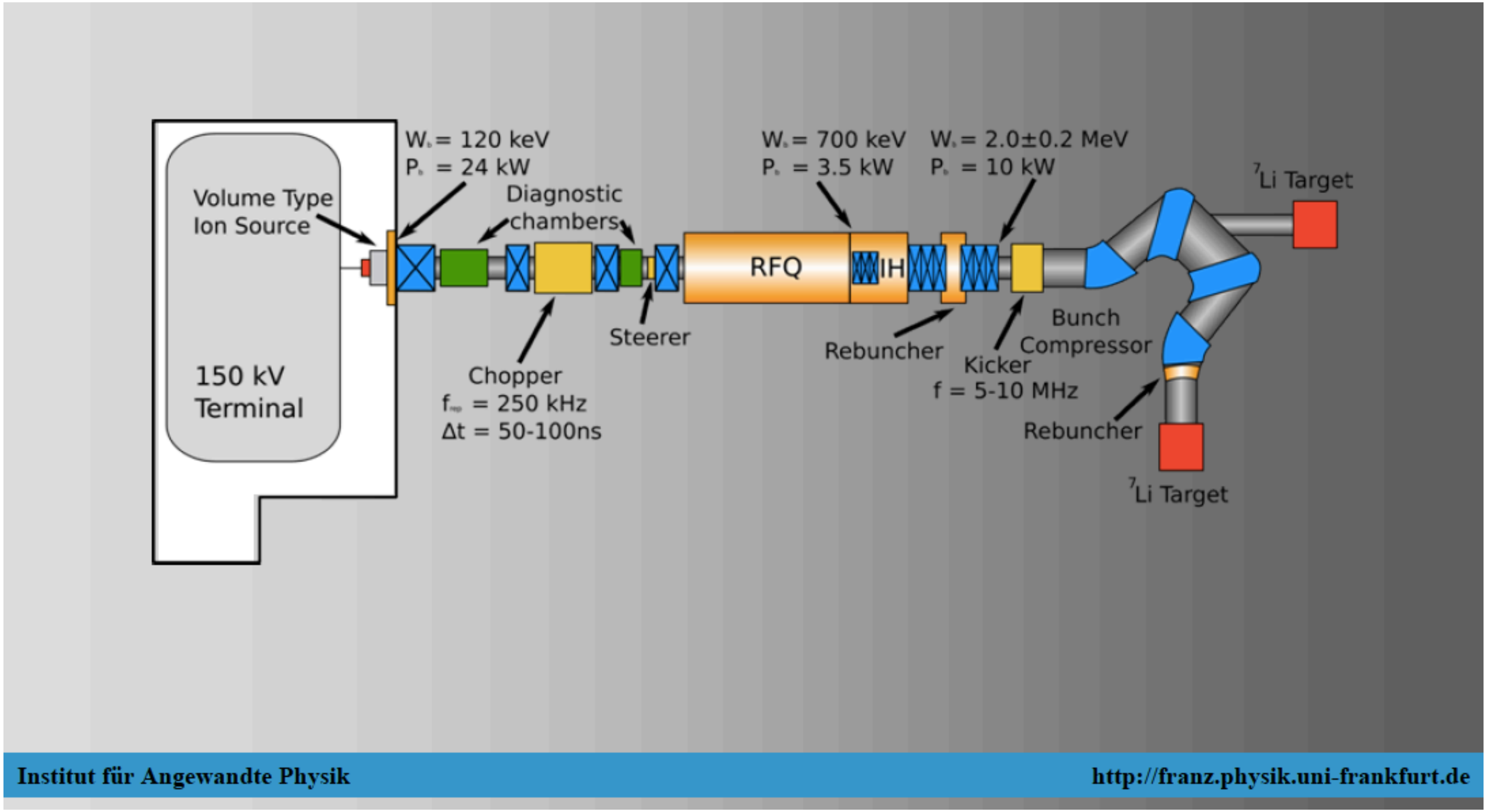
$$\left(2I_x+1\right)\left(2I_X+1\right)\left(k_\beta\right)^2\sigma\left(\beta\rightarrow\alpha\right)=\left(2I_y+1\right)\left(2I_Y+1\right)\left(k_\alpha\right)^2\sigma\left(\alpha\rightarrow\beta\right)$$



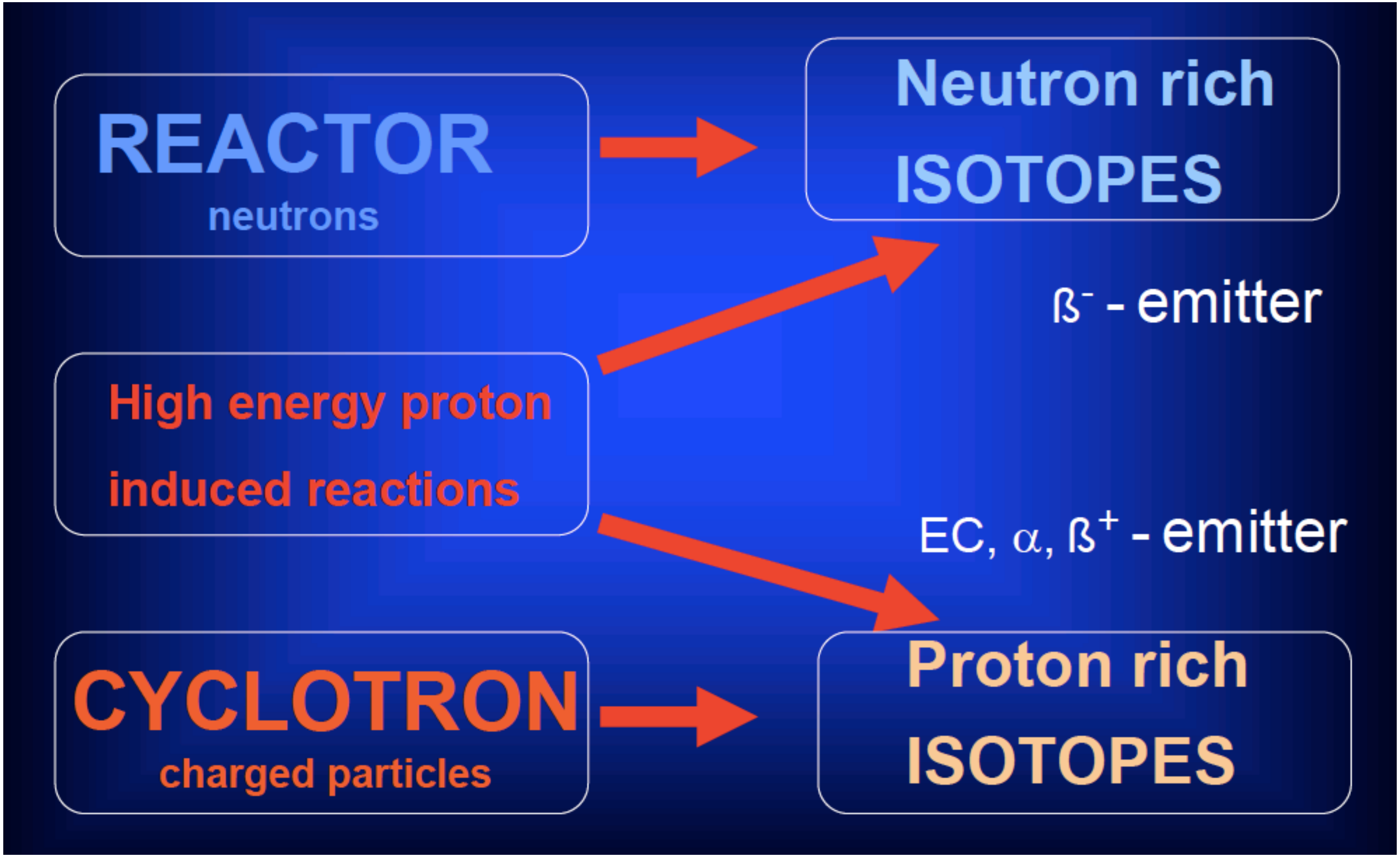
Cross sections obtained by CANS

Angulo

Frankfurt Neutron Source – FRANZ, Under Construction



Other Applications: Isotope Production



Supply Problem of $^{99M}Mo/^{99}Tc$ Isotope for Medical Use

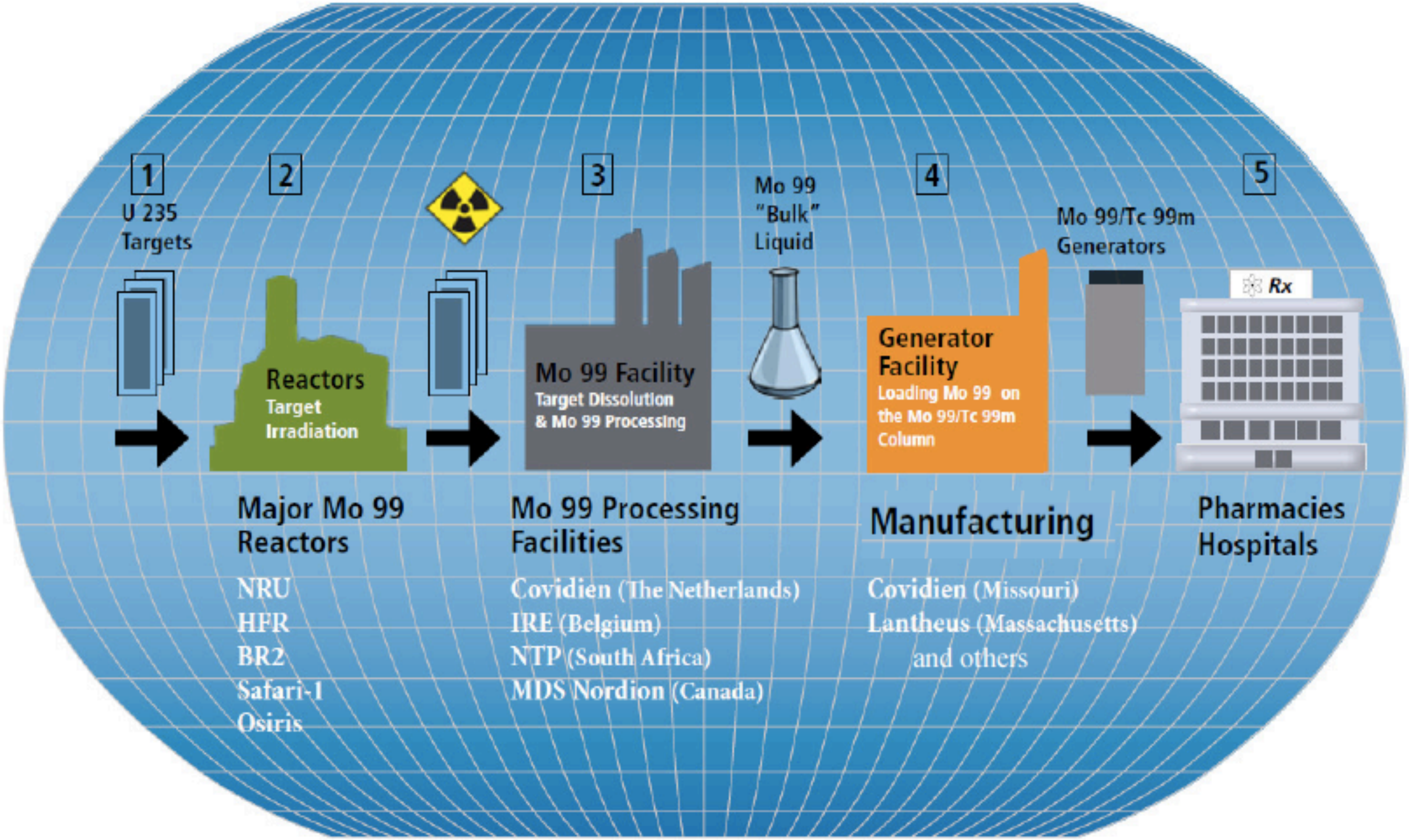
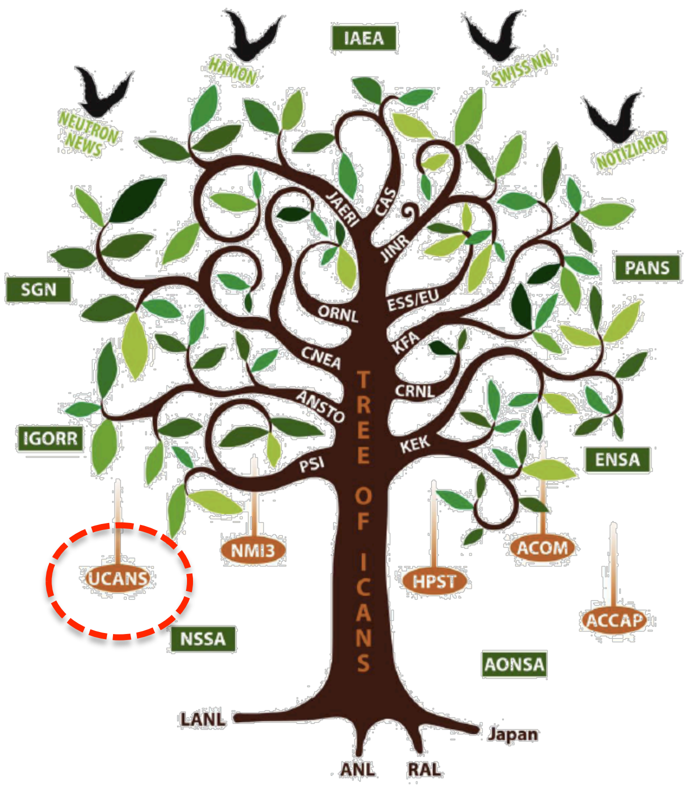


FIG. VII-1: Global supply chain of ^{99}Mo and subsequent utilization schematics. Source: www.covidien.com (October 2009)

Union for Compact Accelerator-driven Neutron Sources (UCANS) Established in 2008



UCANS-IV, Sapporo, Hokkaido, Japan Sept 23-27, 2013


School & Meeting Reports

http://neutronielucedisincrotrone.cnr.it/

THE FOURTH MEETING OF THE UNION FOR COMPACT ACCELERATOR-DRIVEN NEUTRON SOURCES (UCANS)

Yoshiaki Kiyanagi Hokkaido University, Japan
Chun.-K. Loong The NAST Center, University of Rome Tor Vergata, Italy.

Michihiro Furusaka of Hokkaido University and Jose Rolando Granada of the CNEA, Bariloche (at central front) are seen to engage in ruminative discussion during the poster session.

UCANS-V, Univ. Padova, Italy, 2015

Bring a theme of CANS to Erice SoNS, 2015 (?)

CANS in Italy

Andreani

Name Type	Energy/Current Primary Particle	Target	Reaction	Neutron Intensity (S^{-1})	Merits/Characteristics	Complementarity
TAU/ CHARM *e*-Linac	2.9 GeV	Pb	Photo production	1.9 $\times 10^{13}$ (no D_2O) 2.4 $\times 10^{13}$ (10cm D_2O)	full spectrum of cold-thermal-epithermal-fast neutrons; short pulse allows high resolution experiments with conventional TOF techniques	Multi-purpose studies; short-pulse low-E diffraction + imaging allow concurrent measurement of crystal phases, strains, texture, and imaging; penetrative fast-neutron imaging of very large objects; capture gamma over all neutron energies
		W		3 $\times 10^{13}$		
		^{238}U		5.3 $\times 10^{13}$		
IRIDE *e*-Linac	1 GeV	W	Photo production	1.0 $\times 10^{15}$	full spectrum; long pulse structure	Long pulse structure requires long flight path and multiple choppers for needed resolution
SPES-cyclotron proton	70 MeV, 0.5 mA upgrade to 1mA	W	W(p,xn)	2.8 $\times 10^{11}$ [5.6 $\times 10^{14}$ CW]	quasi-monoenergetic neutrons (un-moderated); low yield using low-Z targets; CW or long pulse	Single or special purposes; accelerated test chip irradiation + low-E SANS & reflectometry
	35-70 MeV 50 μA	thin Be or Li	Li(p,xn) Be (p,nx)	3 $\times 10^{6}$ at 3.5 m	quasi-monoenergetic neutrons (un-moderated); proton energy below spallation threshold, low yield using low-Z targets; CW (see figure on right)	
	70 MeV 0.5 mA	rotating composite thick Be/Pb or Be/Ta	Pb(p,xn) Be(p,nx)	4.84 $\times 10^{13}$ 3.75 $\times 10^{13}$		
TRASCO-RFQ *p*-linac	5 MeV 50 mA	thin Li	^{7}Li(p,n)		compact, less expensive, CW or long pulse; low flux sources	Good for education & instrumentation development
	5 MeV 30 mA	thick Be	^{9}Be(p,xn)	1.0 $\times 10^{14}$		

Thank You

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Questions